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Field Manual for Oil Spills in Cold Climates

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FIELD MANUAL FOR OIL SPILLS IN COLD CLIMATES

by

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components requires a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report is a field manual intended for use by On-Scene Coordinators (OSCs) responding to oil spills in cold regions. The manual documents the state-of-the-art response techniques as of early 1979. The first part of the manual consists of matrices which summarize applicable response techniques for various conditions, while the remainder contains supporting and amplifying documentation for the first part. For further information on the subject of this report, contact the EPA Oil & Hazardous Materials Spills Branch, Edison, New Jersey 08817.

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ABSTRACT

The probabilities for the occurrence of oil spills are increasing along with our growing need to exploit the natural resources of the arctic and other cold regions. The technology used to respond to oil spills in cold regions has been evolving rapidly, but effective responses cannot yet be achieved in all environmental conditions for all types of oil. This manual documents the state-of-the-art response techniques as of early 1979.

The manual has been divided into two basic parts: A field manual (Section 2) and supporting data (Sections 3 through 12). The field manual consists of a set of matrices that summarizes applicable techniques for various conditions. The on-scene coordinators will be able to use the matrices as a quick reference while they are responding to spills.

The supporting data in the second part of this manual give a detailed summary of information on oil behavior and cleanup techniques. In the preparation of this manual, it was assumed that on-scene coordinators would have the opportunity to become knowledgeable enough about the material in this section so that only quick references to the field manual would be needed while responding to spills. It is also hoped that the on-scene coordinators will have had time to gather the information suggested (for example, maps delineating habitats and access roads) before the spill occurs. The ultimate success or failure of a response to an oil spill in cold regions will largely hinge on the on-scene coordinator's understanding of the information presented here and on his knowledge of the area in which the spill occurred.

In a fast-moving technology, a manual documenting accepted practices will be shortly outdated. Thus the reader is cautioned that newer philosophies, techniques, and equipment than those discussed in this publication may be available.

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SECTION 1

INTRODUCTION

As the recovery of natural resources in cold regions becomes more economical because of rising market values for these products, increased insults from oil spills in these areas become inevitable. Two potential sources exist for environmental impacts from oil: exploration for and production of petroleum, and marine or terrestrial transport of both petroleum and nonpetroleum oils.

The technology for extracting resources and for working in cold regions is rapidly advancing. Though the capabilities for responding to spills of oil are also improving, much is unknown about the impacts of oil and about how to minimize or mitigate them. This manual provides current information (as of early 1979) on how to respond to cold-region oil spills. The purpose for writing this manual was to consolidate available literature and expertise on protection, cleanup, and restoration of ocean, estuarine, and inland cold climates and cold weather shorelines endangered or contaminated by oil spills.

The manual has two main parts: A field manual (Section 2) and supporting information (Sections 3 through 12). Though these parts have been bound together for ease of distribution, it is intended that they be separated for use. Section 2, the field manual, consists of matrices and other summarizing tables as well as a practical example of their use. The matrices and tables are provided to give the on-scene coordinator (OSC) the information that is needed for rapid response to spills of oil. Backup information on items mentioned in the field manual matrices can be located via the detailed Table of Contents.

In many spill situations, logistics will constrain the response effort. The on-scene coordinator will have to make decisions regarding the utilization of limited resources to effect the maximum protection benefit. Determining priorities for response is not a simple analytic process but one that has many parameters to be evaluated and compared with each other. Parameters include the major areas of: vulnerability of a coastline to impacts; the potential for biological impacts; and the potential for social, economic, and political impacts on man in terms of recreation, industrial, and natural resources. Given limitations on time, manpower, and equipment, the OSC must have some means of ordering the priorities for protecting these three resource types. In some situations, the solutions will be obvious; in others, careful consultation with local experts will be necessary.

Cold regions appear to have much longer recovery times than warmer climates, making protection of critical resources very important (Vandermeulen, 1978). Seasonal influences also will have an impact on the priorities for protection. For example, in summer a recreational beach may be given a higher value for protection than a waterfowl nesting area, where the birds have left the nest and may not return until next spring. (Of course, the marsh would need to be cleaned before the birds returned.) Many decisions must be left for the individual OSC, his/her staff, and local scientific experts to make within each region.

The OSC will have roughly gauged the extent of the cold-climate oil spill problem when first called to the scene. This should enable him to specify the disciplines in which expert advice may be needed, and hence to gather together an on-scene panel of advisors in those disciplines. The function of the panel members would be to offer information in their areas of expertise to the OSC, and be available as resource persons and to answer his questions. While actual decision-making rests with the OSC, he may choose to involve the on-scene advisors to any extent he deems useful to the optimum response to the oil spill. Certainly, the advisors should gather data for effective use of this manual.

In order to assign priorities for protection within any region, certain data must be gathered. The most compact and useful way of assembling these data is in visual form on maps. Suggestions for maps needed by the OSC are presented below:

1. Base maps -- governmental boundaries, access roads, shipping lanes.

2. Overlay maps -- physical characteristics and land and water use of shoreline, including wind, current, and tide information.

3. Biological resources/seasonal maps showing data on fishes, shellfish, birds, endangered species, marine mammals, and marshes. Emphasis to be on fishing areas, spawning grounds, and habitats.

Maps should be on a scale of 1:50,000, with larger-scale maps for special areas. Maps should be in an easily reproducible size, in black and white. Data should be gathered first on areas with high probability of spill occurrence and then on other areas, as time permits.

Information presented in Sections 3 through 12 covers the details of oil properties, oil behavior in cold environments, cold-region response techniques and equipment, logistics, and restoration considerations.

Familiarity with the information in Sections 3 through 12, coupled with detailed information about the transportation problems, environmental constraints, and availability of equipment, will allow the OSC to respond most effectively to a spill. As he reads Sections 3 through 12, the potential OSC should continuously ask himself, "What would be my response to a spill at this location under these conditions?" The site-specific information that he will need to answer this question should be gathered before a spill occurs. Information that would be useful includes maps of access roads, maps delineating coastal habitats (especially rare, endangered, or threatened species), location of response equipment, and maps showing direction and speed of coastal currents. Reading Sections 3 through 12 will make the potential OSC aware of the needs for various types of information and for the types of considerations that must guide him in the decision-making process.

Sections 3 and 4 present a discussion of oil properties and the changes they undergo in various environmental conditions. Through weathering and biodegradation, the properties (density, viscosity, etc.) of spilled oil change. As these changes occur, the interactions between oil and biota change, as do the techniques required to respond to a spill. Thus the OSC must be aware of the changes, and to some degree, he must be able to predict them and how they will affect the response effort.

The sections on response (Sections 5 through 8) are subdivided into techniques that apply to aquatic, coastal, and terrestrial environments. The sections on transfer (Section 9) and disposal (Section 10) do not follow the outline, as techniques for these are less dependent on the location of the spill.

Logistics considerations are briefly discussed in Section 11. Ultimately, the success of responding to an oil spill will depend on the ability to get equipment and personnel to the scene and to keep both operating effectively. Transportation requirements and the housing and survival needs of personnel are discussed.

Section 12 addresses restoration. Although the OSC will not be involved directly with any restoration efforts, restoration can be made easier by the types of response that the OSC employs. Much effort can be saved in the restoration process if the response techniques have not damaged the area to be restored. Unfortunately thereis little information on restoring coastal or wetland areas in cold climates.

Besides determining the priorities for protection or cleanup response, the OSC must determine the larger question of whether or not any response should be made at all. In some situations, responding to a spill may be more hazardous to the environment (or to the responding crew) than the impacts of the oil spill itself. There is no easy method to prescribe how such decisions should be made. The OSC must understand the appropriate response techniques, the impact that the response and the oil have on the environment, and the fate of the oil if no response is initiated. The information provided in this publication will help the OSC make these decisions, but oil spill experience and knowledge of the particular areas to be impacted are the essential prerequisites.

SECTION 2

FIELD MANUAL

USE OF THE FIELD MANUAL

The field manual is a set of eight matrices (Tables 1 through 8) designed for use by the OSC and his/her staff in the field. These matrices are devoted to the spill response actions in the chronological order generally found necessary. The techniques of response to cold-region oil spills are listed for various environmental conditions and/or oil characterizations. Sections 3 through 12 contain technical backup material paralleling the matrices, as follows:

Table 1:	Oil characterization tests	Section 3:	Oil Properties
2:	Detection and surveillance techniques	4:	Oil spill behavior in cold regions
3:	Electromagnetic surveillance	5:	Surveillance
4:	Containment	6:	Containment
5:	Recovery of low/medium viscosity oils	7:	Recovery
6:	Recovery of high viscosity oils	9:	Pumping systems
7:	Methods of temporary storage	8:	Temporary storage
8:	Disposal techniques	10:	Disposal
		11:	Logistics
		12:	Restoration

The next subsection discusses the matrices in more detail, and the last subsection contains an example that illustrates the use of the field manual.

DECISION MATRICES

The first matrix (Table 1) is an oil characterization test. Qualitative tests are suggested that will allow the OSC to estimate the viscosity range of the spilled oil. The interaction of oil with the environment and the techniques for recovering spilled oil depend on the oil's viscosity. Information on the type (and viscosity) of the oil may be available from the party from whom the oil escaped. However, since the oil characteristics change with ambient temperature, weathering, biodegradation, etc., the characteristics of the oil at the time of the spill response may be different from those at the time the spill occurred. Periodic testing is needed to ascertain whether or not significant changes have occurred, since these changes may necessitate a different response strategy. Laboratory tests of oil properties may be desirable, especially from the scientific aspect of learning more about the rates of change of properties under various conditions. However, the simple tasks outlined in the first matrix should provide the OSC with the information needed to respond to the spill.

Surveillance techniques are outlined in Tables 2 and 3. Table 2 lists applicable techniques for oil spilled under different environmental conditions. Table 3 gives additional information on electromagnetic methods of detection and surveillance. It lists the equipment that can provide useful data under limiting conditions such as darkness, high sea state, cloud cover, and presence of ice or flotsam.

For containment of oil spills (Table 4), as for surveillance, the applicable methods have little dependence on the oil characterization. Containment methods include using specially designed equipment and building barriers of naturally occurring materials (for example, snow or sand). The matrix in Table 4 lists various environments in which spilled oil may occur and recommends containment methods.

Information on the recovery of oil has been summarized in two matrices (Tables 5 and 6). Table 5 covers both low- and medium-viscosity oils (refer to Table 1 for definitions of oil viscosity ranges). High-viscosity oils are treated in Table 6. Checks in the body of the matrix denote which techniques are recommended for the various environmental conditions.

See the Contents page for location of data on the recovery devices and techniques in Section 7.

The information on temporary storage (Table 7) is categorized according to the environment (aquatic or coastal/terrestrial) and nature of the storage type (deployed by air or surface vehicles or utilizing natural features or materials). Storage type is independent of oil characterization.

The last matrix (Table 8) is a summary of disposal techniques. Though the success of these methods depends to some degree on the type of oil to be disposed, there are other factors that can limit the effectiveness of disposal. The most important of these factors are the types and quantities of material mixed with the recovered oil.

The matrices have been designed to provide a quick reference to the technical material in response to cold-region oil spills. It is hoped that they will be a valuable information source for the coordinator at the scene of an oil spill. However, it must be realized that in many incidents, the response to an oil spill will be controlled by the availability of equipment, manpower, and other resources. Non-optimum methods will be employed because of the lack of optimum methods or the inability to bring in sufficient quantities of needed resources in a realistic time scale. Thus though the OSC may find the matrices useful at a spill site, the ultimate success of response will depend on the availability of needed resources and the OSC's in-depth knowledge of techniques and oil behavior in cold climates. Such a greater level of understanding can be derived from this manual and from experience at spills.

A detailed Table of Contents has been provided for ease in locating specific items in Sections 3 through 12 to elaborate on Tables 1 through 8.

TABLE 1. OIL CHARACTERIZATION TESTS

Characteristic viscosity*	Visual appearance	Adheres to surfaces	Ability to pour or spread	Measured kinematic viscosity (Centistokes)	Other
Low	Clear or translucent	Does not adhere	Pours easily, spreads rapidly	< 200	Evaporates quickly, strong odor
Medium	Variable	Adheres but can be cleaned by flushing, forms thin coat on surface, feels waxy	Pours sluggishly	200 to 300,000	Mild odor
High	Black or dark color, opaque	Forms thick coat on surface, cannot be removed by agitation, feels sticky	Does not pour, may form tar balls	$> 300{,}000$	May sink in water

* The viscosity of the spilled material dictates how it will move through the environment, how it affects plants and animals, and how it can be removed. It is important to note that the viscosity of oil changes with temperature and weathering. Thus the characterization of spilled oil may change, and response activities may also need to be changed.

TABLE 2. DETECTION AND SURVEILLANCE TECHNIQUES

Environment of condition	Detection and surveillance techniques
Aquatic	
Open water	Visual Electromagnetic (EM)
Ice present	
Oil exposed on surface	Visual EM
Oil not exposed	Use augers or drills Visually by SCUBA divers Impulse radar
Terrestrial (Shorelines)	
Exposed on surface	Visual
Buried in sediment	Use augers or drills
In Snow	
Exposed on surface	Visual
Oil covered by snow	Manual probing Gas analyzers

TABLE 3. ELECTROMAGNETIC SURVEILLANCE: USEFUL DEVICES IN LIMITING ENVIRONMENTAL CONDITIONS

Lighting conditions	Environmental condition			
	High sea state	Cloud cover	Flotsam present	Ice present
Daylight	Photography	Microwave	Low-light-level television	Photography
	Ultraviolet line scanner	Side-looking airborne radar	Photography	Thermal infrared line scanner
	Thermal infrared line scanner			Forward-looking infrared
	Forward-looking infrared			
	Microwave			
	Side-looking airborne radar			
Night	Thermal infrared line scanner	Microwave	Microwave	Thermal infrared line scanner
	Forward-looking infrared	Side-looking airborne radar		Forward-looking infrared
	Microwave			
	Side-looking airborne radar			
	------ Lasers are useful in all conditions ------			

TABLE 4. CONTAINMENT

Environment	Containment Method
Aquatic	
Shorefast Ice	
On top of ice	Berms Sorbent booms
Below ice	Slot Ice barrier Slot and boom Cut and deep-skirted boom
Sandwiched in decaying ice	Wait until rises, trenches
Fractured/Deformed Ice	
Rafted/piled	Occurs naturally
In leads	Conventional booms
Ice Floes	
<20% concentration	Conventional booms Ice-oil boom Bubble barrier
20-80% concentration	Oil-ice boom
>80% concentration	-----
Coastal	
Rocky Coast or Cliffs	-----
Eroded, Wave-Cut Platforms	-----
Flat, Fine Sand	Dike, berm
Steep, Medium-Coarse Sand	Dike, berm
Tidal Flats	-----
Mixed Sand and Gravel	Dike, berm
Gravel Beaches	-----
Sheltered Marshes	-----
Terrestrial	
Tundra	Dike, berm
Rocky Terrain	-----
Forest	Dike, berm, trenching
Grasslands	Dike, berm, trenching

TABLE 5. RECOVERY OF LOW/MEDIUM-VISCOSITY OILS

Recovery technique	Environmental Characteristics																					
	Aquatic										Coastline							Terrestrial				
	Shorefast Ice				Fractured/Deformed Ice		Ice Flow Concentrations															
	On top of	Below	Sandwiched in	In decaying ice	Rafted and piled oil	Leads	<20%	20-80%	>80%	Snow with Oil	Rocky Cliffs	Eroded, Wave-Cut Platforms	Flat Beach, Fine Sand	Steep, Medium-Coarse Sand or Sand and Gravel	Gravel	Tidal Flats	Sheltered Marshes	Snow with Oil	Tundra	Rocky Terrain	Forest	Grasslands	Snow with Oil
Mechanical																							
Disc skimmers						√	√																
Direct suction	√		√		√																		
Ice/snow removal			√						√									√					√
Sediment removal													√	√	√	√							
Steam cleaning and sand blasting											√	√								√			
High-pressure flushing											√	√								√			
Low-pressure flushing																	√					√	
Nonmechanical																							
In-situ burning	√			√	√	√			√														
Sorbents	√			√	√						√	√	√	√									
Dispersants						√	√	√															

√ Indicates techniques that are recommended for the various environmental conditions.

TABLE 6. RECOVERY OF HIGH-VISCOSITY OILS

	Environmental Characteristics																									
	Aquatic													Coastline								Terrestrial				
Recovery technique	Shorefast Ice	On top of	Below	Sandwiched in	In decaying ice	Fractured/Deformed Ice	Rafted and piled oil	Leads	Ice Flow Concentrations	<20%	20-80%	>80%	Snow with Oil	Rocky Cliffs	Eroded, Wave-Cut Platforms	Flat Beach, Fine Sand	Steep, Medium-Coarse Sand or Sand and Gravel	Gravel	Tidal Flats	Sheltered Marshes	Snow with Oil	Tundra	Rocky Terrain	Forest	Grasslands	Snow with Oil
Mechanical																										
Ice/snow removal		√											√								√					√
Sediment Removal																√	√	√	√						√	
Steam cleaning and sand blasting														√	√								√			
High-pressure flushing														√	√								√			
Low-pressure flushing																				√					√	
Slotting			√																							
Nonmechanical																										
In-situ burning			√		√		√	√				√														
Sorbents			√		√		√							√	√	√	√									
Dispersants										√	√															

√ Indicates techniques that are recommended for the various environmental conditions.

TABLE 7. METHODS OF TEMPORARY STORAGE

Storage type	Aquatic	Coastal/terrestrial
Surface vehicles	Ships, tanks, and barges	Vacuum trucks, tankers, flatbeds with bladders and drums
Air-deployable systems	Pillow bags, donuts	Pillow bags, open top containers
Environmental features	Lakes, lagoons, shorefast ice, snow on ice berms	Lagoon pits, dikes, snow on ice berms

TABLE 8. DISPOSAL TECHNIQUES

Type	Limitations
Mechanical	
Flare burners	Little debris tolerance
Open-pit incinerators	-----
Rotary kiln	Solids only (oil and sediment)
Stoker incinerators	Combustible solids
Salvage	
Pipeline reinjection	Relatively clean oil
Inject to well	Limited debris
Refinery	Clean oil
Direct reuse	-----
Land Disposal	
Land cultivation	Seasonally limited
Landfill/solid waste	Dependent on local regulations
Burial	-----

EXAMPLE OF USE

To illustrate the use of this manual, an example of an oil spill is described and the decision matrices are applied. The example used is the Buzzards Bay oil spill of 1977, which was one of the few spills in ice that has occurred in the lower 48 States where a major response effort was mounted.

At 1800 hours on 28 January 1977 the barge Bouchard 65, carrying 12,100 m^3 (3.2 million gallons) of No. 2 heating oil, ran aground on Cleveland Ledge in Buzzards Bay, Massachusetts. Four of the barge's tanks were holed. At 2030 hours the barge was floated off the ledge and towed to Wings Neck, where it was intentionally run aground to stop the leakage. Following off-loading, the barge was towed through the Cape Cod Canal to Boston (see Figure 1). Approximately 307 m^3 (81,000) gallons of oil were spilled (Baxter, et al., 1978).

Icing conditions at the time of the spill are shown in Figure 2. The active ice zone consisted of an 80% to 100% surface areal coverage of ice floes and rafted and piled ice. Ice thicknesses were between 0.3 and 1.2 m (1 to 4 ft). Air temperatures ranged from -13° to 3°C (8.6 to 37°F); wind speeds varied from 3.7 to 64.6 km/hr (2 to 35 knots) in the first 2 days of the spill.

If the OSC had been provided with this document at the time of this spill, he would have proceeded in the following manner.

Step One: Spilled Oil Characteristics

First, determine oil characteristics to judge potential for movement, cleanup, and disposal processes. Tests with the oil indicated that it is clear, pours easily, spreads quickly, does not adhere to surfaces, and has a strong odor. Turning to the matrix on oil characterization, the OSC finds that this is to be treated as a low-viscosity oil (Table 1).

Step Two: Resources to be Protected

The OSC next must consider the resources that must be protected in this area. In talking to local experts, he finds out that in Buzzards Bay the areas along Wings Neck north to Phinneys Harbor are prime shellfish production areas for the local fishermen. There are no major marsh systems, but waterfowl winter in the bay. A large number of resort homes located along Wings Neck and Scraggy Neck are occupied only in the summer. It can be seen by looking at the map that little can be done to protect the shoreline areas because they are encased in shorefast ice, and the area is too large to boom off in any fashion. So, no protection measures will be taken. If protection had been possible, the shellfish production areas would have received first priority because of their prime economic importance.

Step Three: Spill Surveillance

Surveillance of the spill is a task that must be continued throughout cleanup operations. The oil has been spilled in an aquatic environment where

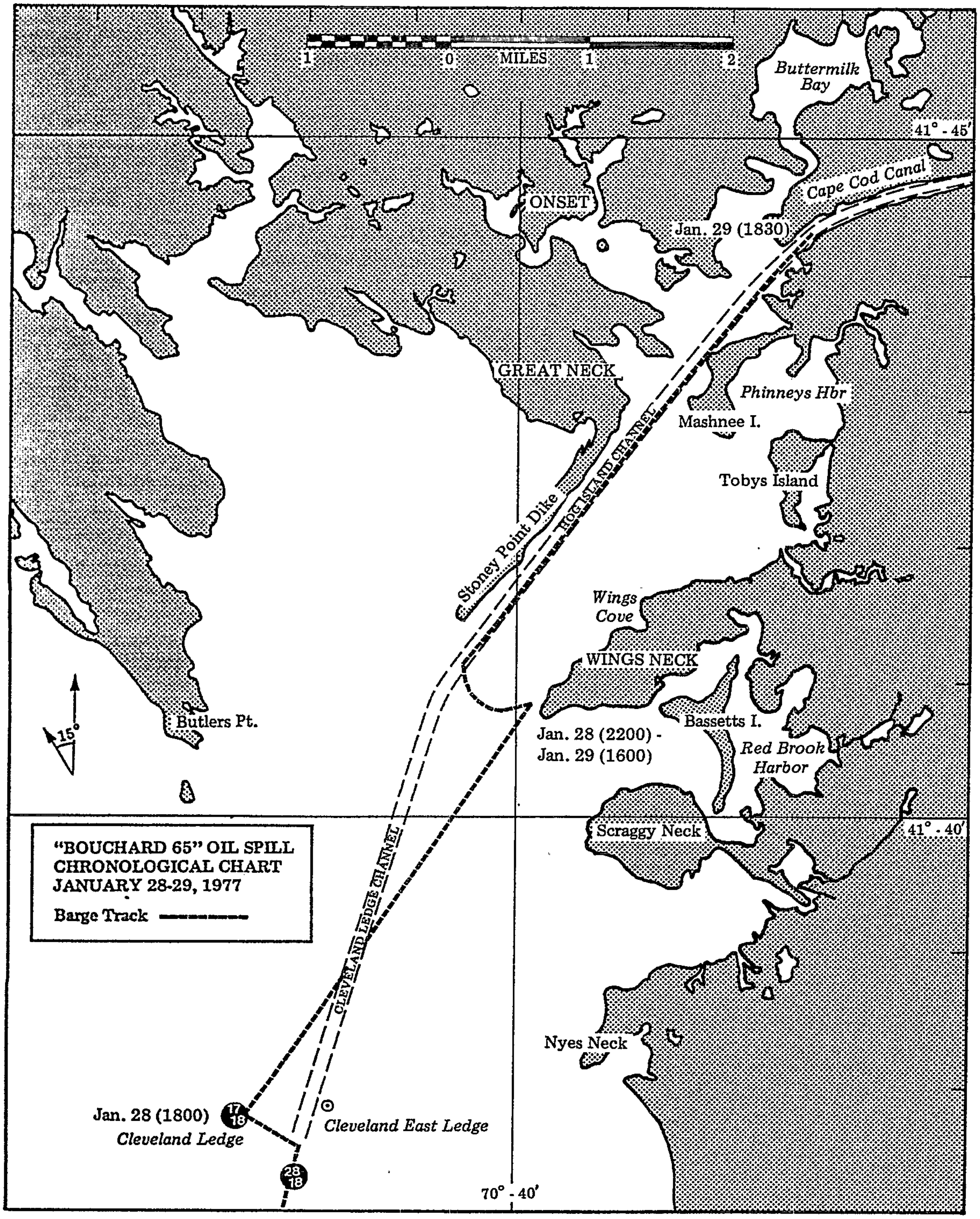


Figure 1. Bouchard 65 oil spill chronological chart.

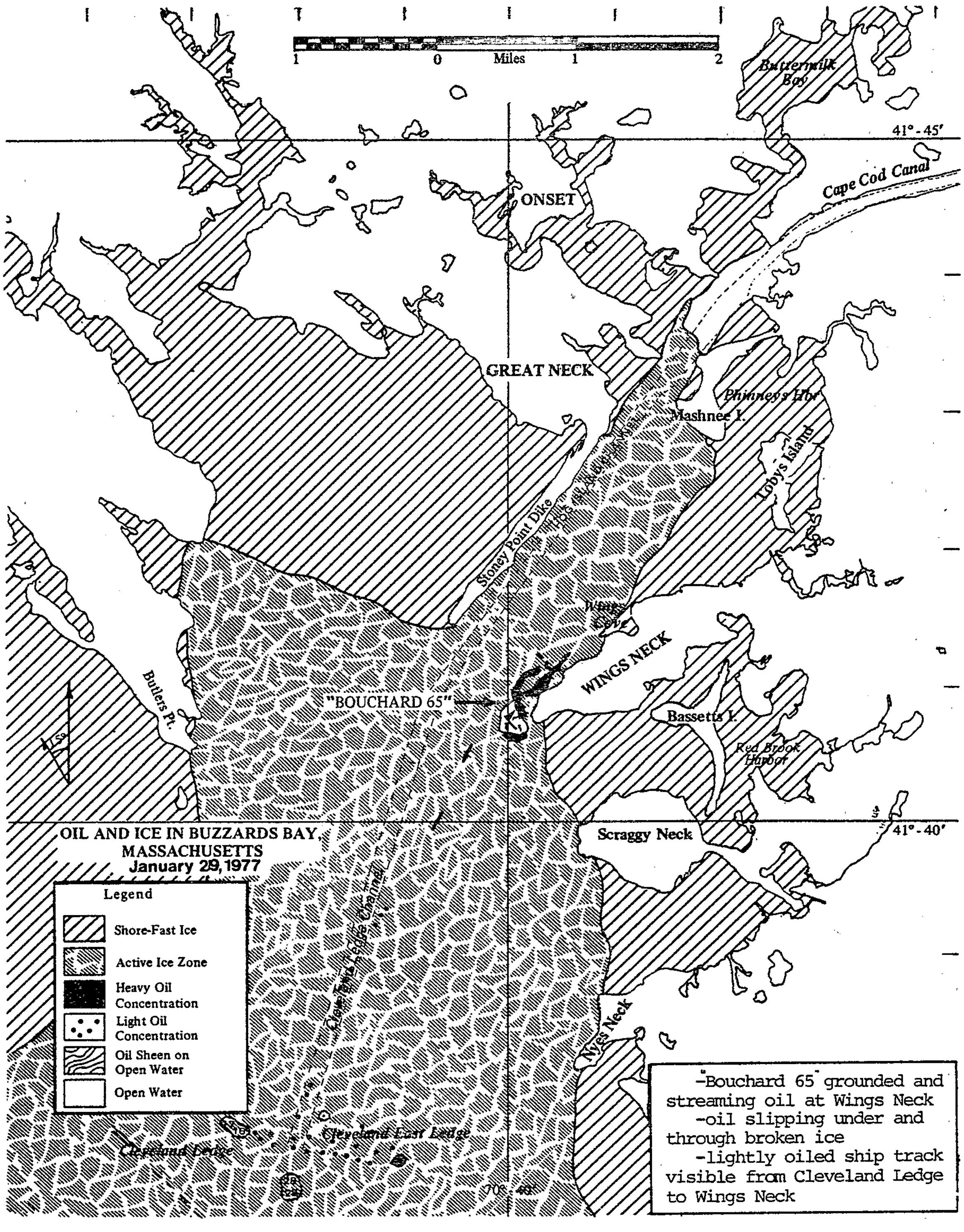


Figure 2. Oil and ice in Buzzards Bay, Massachusetts, January 29, 1977.

oil is both exposed and hidden in ice. Looking at the detection and surveillance matrix (Table 2), the OSC discovers that he may use visual or electromagnetic devices for exposed oil. For hidden oil, augers and drills, impulse radar, and SCUBA divers may be used (Table 2).

The electromagnetic devices (Table 3) are also outlined according to the limiting environmental conditions. In this situation, photography would be the best electromagnetic technique.

In the Buzzards Bay spill, drills, augers, impulse radar, and visual techniques were used, with varying degrees of success. Daylight photography was the only electromagnetic device employed. Visual observation was often obstructed because of high winds, fog, and cloud cover. In addition, problems were found with motor-driven augers because of the extremely cold temperatures. Overall, the surveillance options recommended proved useful, within the limits of the equipment availability and usefulness in cold temperatures.

Step Four: Spill Containment

Containment of the spill is the next priority. Since the oil is in rafted and piled ice, in ice floes in concentrations of greater than 80%, and underneath shorefast ice, consulting the containment matrix (Table 4) shows the OSC that containment may occur naturally in rafted and piled ice and is not possible in greater than 80% ice concentrations. For oil beneath shorefact ice, there are several techniques (Table 4).

In Buzzards Bay, the oil was contained naturally. Continuous surveillance of the shorefast ice zones indicated that too little oil was present to warrant any of the more active suggested methods.

Step Five: Spill Recovery

Recovery of the spill may be accomplished next. In rafted and piled ice with a low-viscosity oil, the matrix (Table 5) shows that in-situ burning, direct suction, and sorbents may be useful. In greater than 80% ice flow concentrations, the matrix (Table 5) shows in-situ burning as the only possible mechanism. Oil concentrations under shorefast ice have already been determined to be too low to warrant cleanup.

In the Buzzards Bay spill, direct suction was the primary method used. Problems were found with pumps and hoses freezing. In-situ burning was used at one site with moderate success, but it was not attempted again because of the air pollution problem. Sorbents were not available for use.

Step Six: Temporary Storage and Disposal

Once the recovery process has begun, storage and disposal systems (Tables 7 and 8) must be put into use. The disposal matrix (Table 8) outlines the systems available and their limitations. Since the oil is relatively free of debris, flare burners, any of the salvage techniques, and landfill may be used.

In Buzzards Bay the oil was taken to a refinery and re-refined, and some was transported to a landfill for disposal. Flare burning was not possible because of equipment limitations. No intermediate storage was necessary.

Overview

This scenario shows that the manual can be used for quick and easy reference in the field, with background information quickly available. The background information should be read thoroughly and understood by the OSC before any spill incidents. Decisions can thus be made most effectively in the field. It should be strongly emphasized that the manual can be used effectively only if the OSC and his staff have a thorough knowledge of the local area and the resources and equipment for spill response available therein. This is even more important in remote areas where information is generally less accessible.

SECTION 3

OIL PROPERTIES

The type of spilled oil determines the characteristics needed for optimum response to the spill:

1. Aging rates,

2. Danger of fire and explosion,

3. Biological impact,

4. Spreading, and

5. Penetration into soil, snow, and ice.

These characteristics are related to these measurable oil properties:

1. Specific gravity,

2. Viscosity,

3. Pour point, and

4. Boiling point.

SPECIFIC GRAVITY

The specific gravity of oil is defined as the ratio of its density to the density of water at the same temperature. The density is usually measured in grams per cubic centimeter (g/cm^3). If the density of oil is greater than 1 g/cm^3, it will sink in water. In the petroleum industry, specific gravity is usually expressed in degrees API. The relationship between specific gravity values and degree API at 16°C (60°F) is provided in Figure 3.

The specific gravity will increase with decreasing temperature and with oil aging, as evidenced by evaporation of the most volatile components. Figure 4 illustrates typical variations in specific gravity that occur resulting from temperature and aging. For reliable data on specific gravity, it is best to take measurements at the spill site with equipment such as hydrometers (refer to ASTM Methods E-100 and D-1298).

Information on specific gravity will provide several insights into the oil-spill behavior. Specific gravity will affect the ease with which the oil

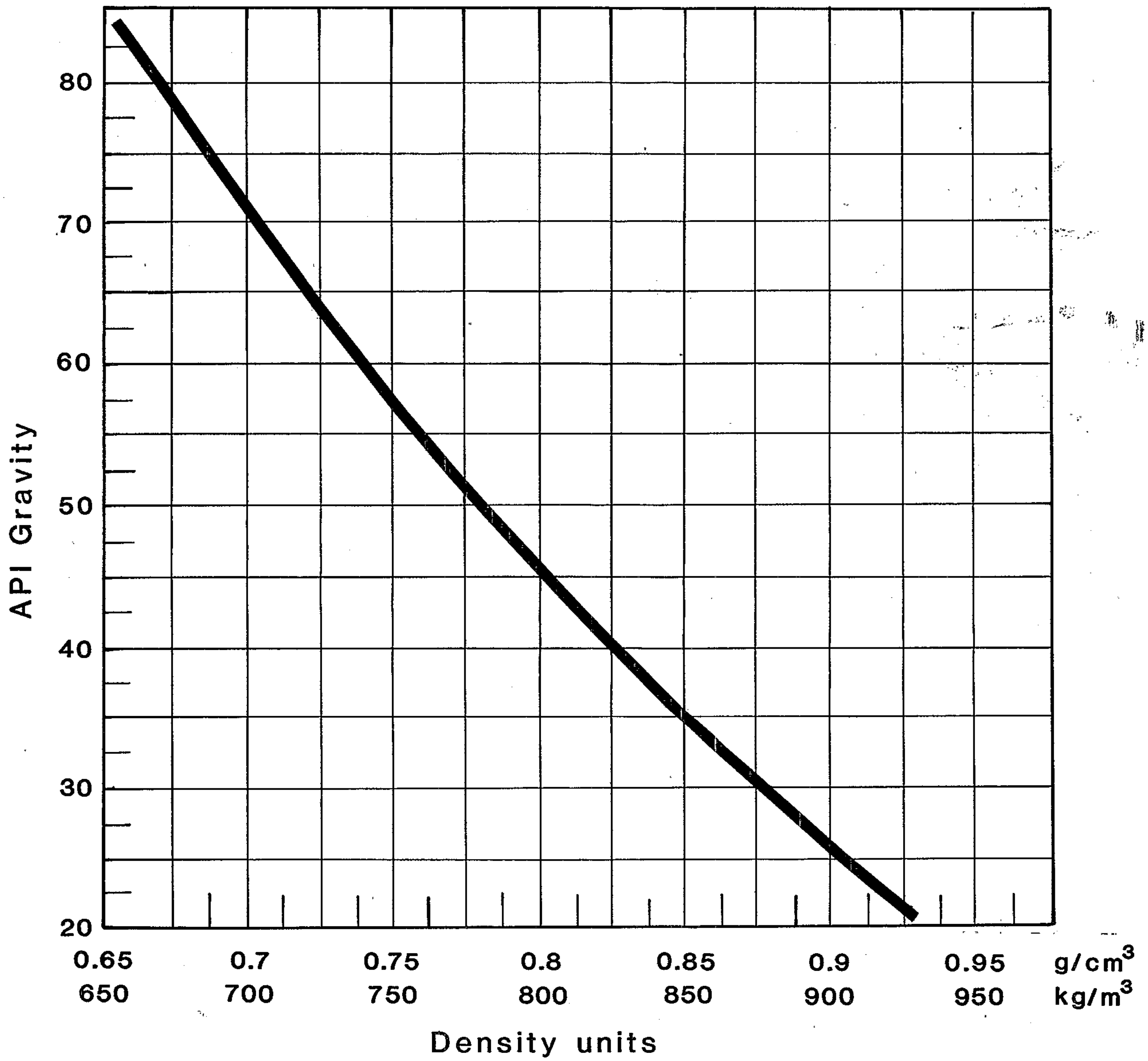


Figure 3. Conversion of API gravities to conventional density units (Nadeau and Mackay, 1978).

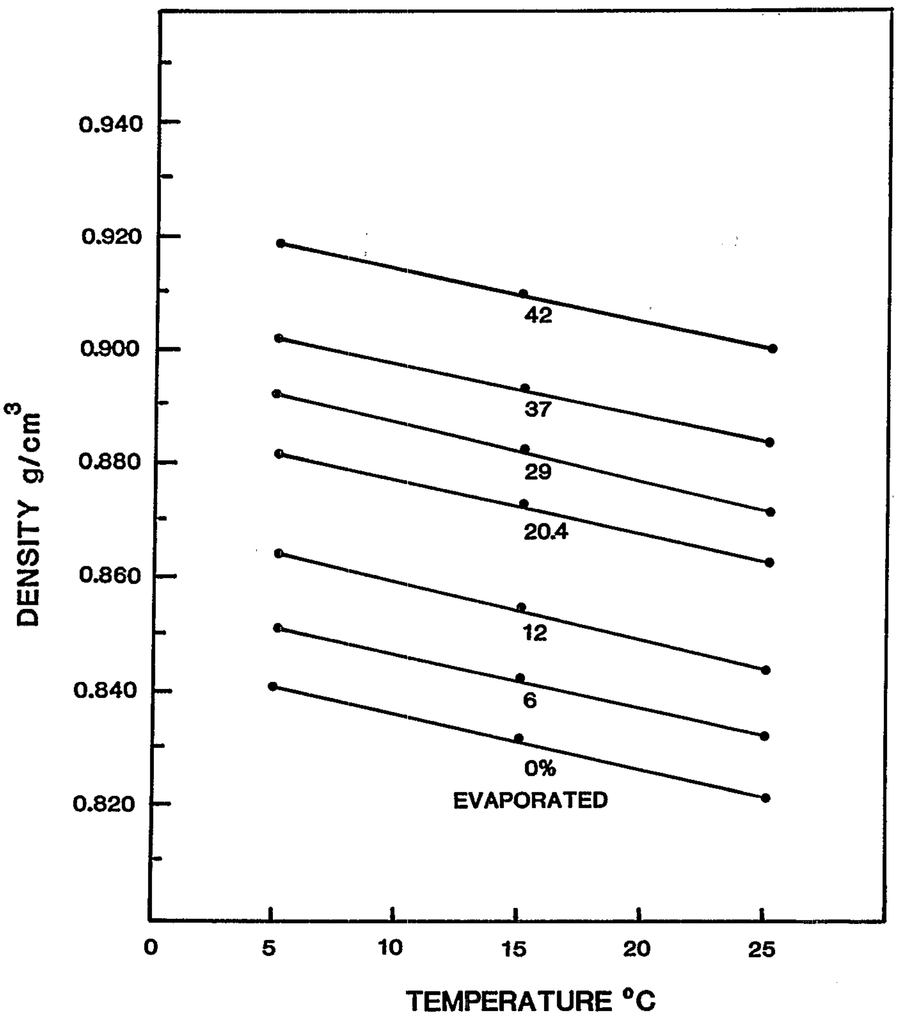


Figure 4. Density of Norman Wells crude oil versus temperature and aging (Mackay et al., 1975).

mixes throughout the water column. When oil has a specific gravity of 0.9 or larger (such as Bunker C or No. 6 fuel oil) the combination of evaporation, cold temperatures, and attachment of mineral particles may cause the oil to sink within a few days. Considerations of specific gravity may also be important in projecting whether oil will spread on top of or underneath an ice cover.

VISCOSITY

Viscosity of a fluid relates to its internal friction or resistance to flow. Oil viscosity is categorized into three ranges, which can be estimated by making a few simple tests (more accurate measurements can be made by instruments, such as a Brookfield viscometer, ASTM Method D -1298):

1. Low Viscosity: pours easily, spreads rapidly, has a strong odor, has a high evaporation rate, does not adhere, is removed by flushing, and is clear or translucent in appearance.

2. Medium Viscosity: pours sluggishly, adheres to surface, can be partially cleaned by flushing, and has a mild odor.

3. High Viscosity: does not pour, has a tarry texture, is very sticky, cannot be removed from surface by flushing, and may sink in water.

Viscosity will change with temperature, oil aging, and emulsion formation. As the temperature drops, oil viscosity will increase (Figure 5). This increase becomes very rapid as the ambient temperature approaches the pour-point temperature. The viscosity will also increase as the oil ages, particularly during the early stages of the spill, because of processes such as evaporation and emulsification. Evaporation is often the most important process that alters the viscosity; a procedure for determining evaporation is discussed later on in this section. The aging of Prudhoe Bay crude oil, for example, may cause the viscosity to change by a factor of 3 or more during the first 24 hours and by a factor of 10 in a week (Isakson et al., 1975). The viscosity changes resulting from a combination of aging and temperature can be significant (Figure 6). For aquatic spills, oil/water emulsions caused by water turbulence may considerably increase the viscosity within a short time (Twardus, 1979a).

Oil viscosity can have a significant impact on the outcome of the oil-spill behavior and preferred cleanup response. The spreading rate of the spilled oil is partially dependent upon the viscosity. Low-viscosity oils spread thinly over ice and water, and high-viscosity oils tend to flow into thick lenses. In addition, the amount of penetration into a surface is partially governed by viscosity. Light or low-viscosity oils tend to be absorbed easily into materials, while highly viscous oils tend to adhere to surfaces.

POUR POINT

Another important measurement (usually provided with the oil specifications) which directly relates to the oil's viscosity is the pour point. This is the lowest temperature at which an oil can be poured.

BOILING POINT OF OIL

The boiling point of oils is directly related to oil aging and explosion and fire risk. Low boiling fractions are volatile and will evaporate readily when exposed to the atmosphere. Simulated evaporative weathering tests, under controlled temperature conditions (Kreider, 1971; Smith and MacIntyre, 1971) indicated that virtually all hydrocarbons with a boiling point of less than 250°C (482°F) will volatilize from the sea surface within 10 days. Many lighter petroleum materials tend to disappear in hours. Hydrocarbons that boil between 250 and 400°C (482 and 752°F) will evaporate in more limited amounts and will, therefore, remain largely in the oil slick. Hydrocarbons that have boiling points greater than 400°C (752°F) will be retained. Since oil is a mixture of many different hydrocarbons, the composition of a

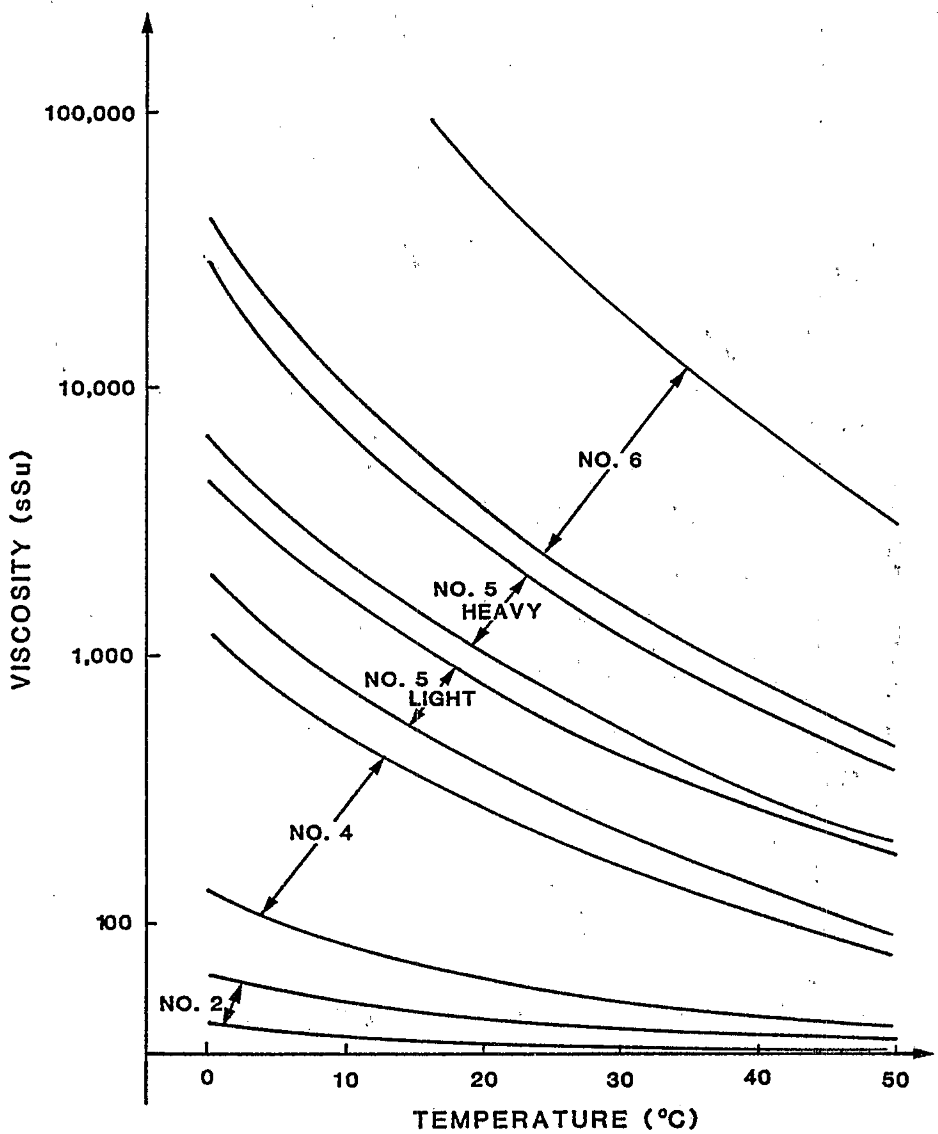


Figure 5. Oil viscosity versus temperature (Mittleman, 1978).

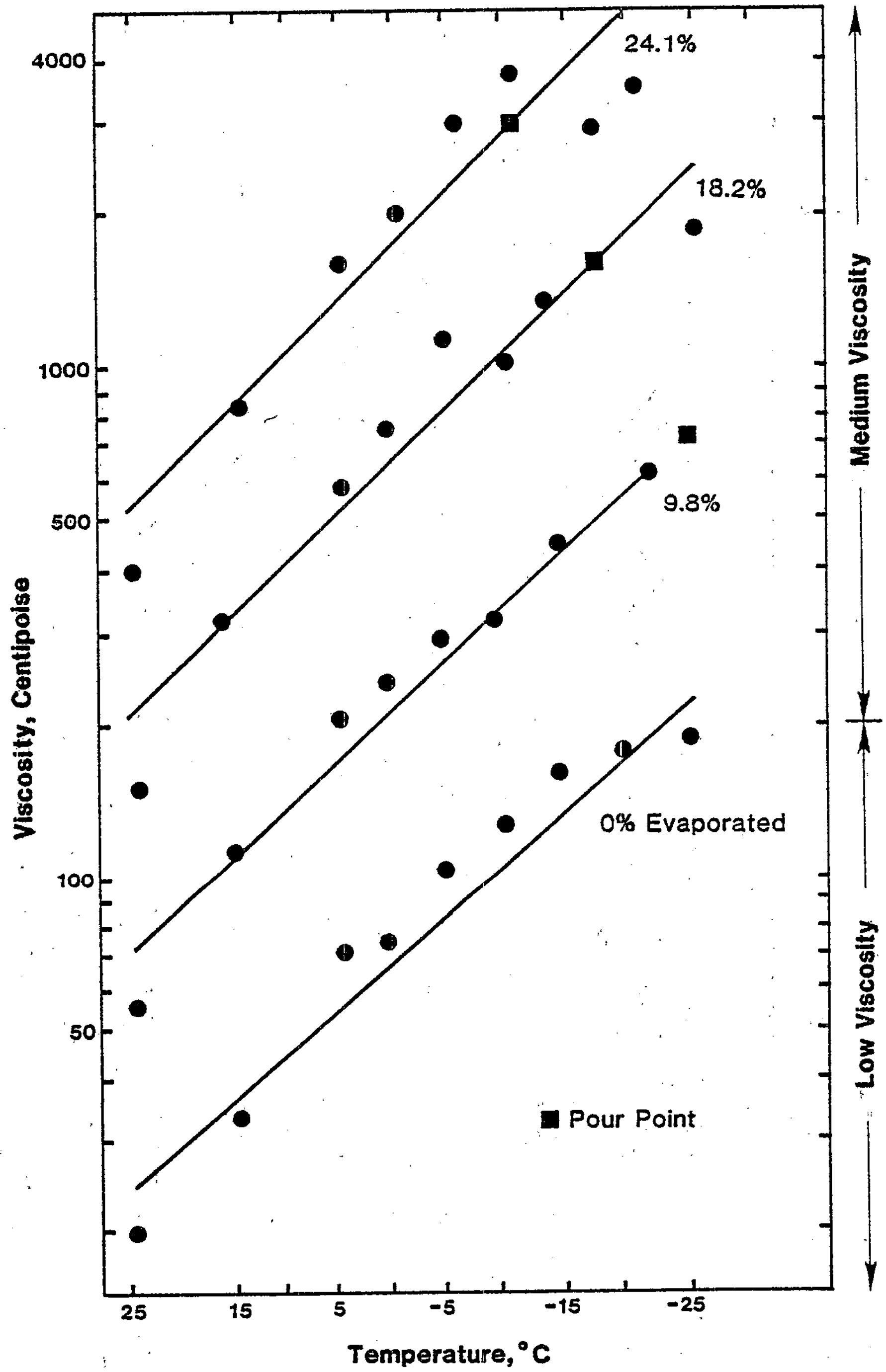


Figure 6. Viscosity of Prudhoe Bay crude oil (Mackay et al., 1975)

particular oil will change while weathering as the various components evaporate at their own rate.

OIL AGING

The aging rate of spilled oil in cold climates is different from that in warmer climates. The low temperatures and presence of ice and snow restrict vapors from escaping. The aging of oil is governed by three types of processes: physical processes, such as evaporation, dissolution, emulsification, and absorption; chemical processes, such as direct oxidation and reduction reactions in the water column; and biological processes, such as aerobic and anaerobic microbial degradation.

During the early stages of a spill, the aging of the oil is primarily a function of the physical process of evaporation. Evaporation occurs when low molecular weight compounds are volatilized into the atmosphere. This process will remove nearly all light distillates and 30% to 50% of typical crude petroleums (Malins, 1977). Therefore, the evaporation rate is important in deciding the actual volume of oil present shortly after the spill and the potential threat to the ecosystem. It will directly affect the specific gravity, viscosity, and toxicity of the oil. Also, fire and explosion hazards will decrease as the lighter, more volatile fractions evaporate.

The evaporation rate for pools of spilled oil on an exposed solid or liquid surface can be calculated using a procedure formulated by Nadeau and Mackay (1978). This calculation can be made from information on the product volatility, wind speed, temperature, and slick thickness. Spilled oil covered by ice or snow or absorbed into ice, snow, or soil will age at a much slower rate than exposed oil. There are presently no aging rate calculations available for these spill situations, but observations from several spill incidents can provide an indication of the expected aging losses.

Deslauriers et al. (1977) reported that No. 2 diesel oil underneath an ice cover with water currents of 1 m/s (3.3 ft/s) had one-fifth the loss of oil from a free surface. NORCOR (1974) observed that losses resulting from the aging of oil underneath an ice cover were in the range of one-ninth of the loss for a sample exposed to the atmosphere over the same period. Ramseier et al. (1973) reported that in a spill involving arctic diesel oil and gasoline, the oil absorbed into the porous ice surface had an evaporation rate of one-fourth of the rate from the free surface. NORCOR (1975) found that oil sandwiched in between ice had a negligible aging loss. When oil is buried in sediments, the oxygen supply is often the rate-controlling factor of weathering. In some anoxic sediments, unweathered hydrocarbons have been observed to be present 7 years after a spill (Teal et al., 1978). Though no systematic studies of cold-region weathering for different snow, ice, and soil interactions have been performed, these preliminary results can be a useful indicator of aging rates.

EXPLOSION AND FIRE RISK

An explosion and fire risk may be present while oil is evaporating at a high rate. To constitute a risk, the escaping hydrocarbon vapor must exceed a certain concentration. This explosion and flammability limit is about 10 torr partial vapor pressure for the lighter hydrocarbons such as gasoline, diesel fuel, and crude oil. Equipment that is not explosion-proof should be used only after a satisfactory explosimeter test when the more volatile hydrocarbons are involved. The usual procedure of containing a spill at or near its source might result in the unnecessary exposure of people and property to explosion and fire risks. There are situations where it may be more desirable to route a flammable product away from its spill source. This may result in some level of environmental impact and/or inefficiency in response; however, such action may avoid an unacceptable risk to human life.

Vapor pressure decreases during evaporation and will drop below the minimum explosion and flammability value when a certain percentage of the oil has evaporated. For gasoline, the vapor pressure at 2°C will drop below 10 torr (mm Hg) when about 60% has evaporated. At higher temperatures, vapor pressure will increase, and so a higher percentage of oil must be evaporated before the explosion and fire risk has passed.

The vapor pressure of a typical medium crude oil falls below 10 torr (mm Hg) for temperatures below 2°C (36°F). At an ambient temperature of 20°C (68°F), only 6% needs to be evaporated before the vapor pressure falls below the flammability limit.

Products such as kerosene, lubricating oil, and high distillates do not possess sufficient vapor pressure to cause an explosion hazard, but they can ignite on floating debris, which acts as a wick. The cooling action of the underlying surface will confine the fire of these products to the area of the wick, except in the case of very thick oil layers. The process of burning oil in situ will be discussed in more detail in Section 10.

Fire-fighting agents may become necessary in some situations. Three agents commonly used in petroleum fires are water, foams, and dry chemicals (American Petroleum Institute, 1974). Water (in liquid form) is universally used as a fire-fighting agent, for cooling, quenching, smothering, emulsifying, diluting, and displacing. Foams for fire protection purposes are an aggregate of gas-filled bubbles that will float on the surface of a flammable liquid. Several foams are available that are principally used to form a cohesive floating blanket on the liquid surface. These foams include the following:

- Protein air foams:
  - Protein foam-liquid concentrates
  - Fluoroprotein foam-liquid concentrates
  - Special-purpose foam-liquid concentrates
- Aqueous film-forming foam
- High-expansion foam
- Chemical foams

The foam extinguishes the fire by smothering and cooling the fuel and prevents reignition by preventing formation of combustile mixtures of vapor and air. Finally, dry chemicals are recognized for their efficiency in extinguishing fires involving flammable liquids. The following finely-divided powders act by inhibiting the oxidation process within the flame itself:

Sodium bicarbonate - ordinary dry chemical

Sodium bicarbonate - foam-compatible dry chemical

Potassium bicarbonate - purple K dry chemical

Potassium oxalate - Monnex

TOXICITY OF OIL

Marine organisms exposed to oil selectively accumulate certain types of hydrocarbons, particularly the aromatic compounds (Varanasi and Malins 1977). Much of the toxicity from oil has been primarily attributed to these aromatic compounds (Anderson et al., 1974) though some recent findings have identified other compounds found in petroleum, including several heterocyclics and nitrogen or oxygen substituted aromatics, to be toxic to certain aquatic organisms (Neff, 1980).

Within an aromatic series, toxicity increases with increasing alkyl substitution on the aromatic nucleus. For example, in the benzene series toxicity increases in the order benzene, toluene, xylene, trimethyl benzene, tetramethylbenzene. Not all organisms are equally sensitive to the aromatic hydrocarbons; in general, the crustaceans have been shown to be the most sensitive; polychaete worms are intermediate; and fish are the most resistant (Neff, 1980). Neff (1980) has summarized the literature with regard to the levels of polycyclic aromatic hydrocarbons that produce acute toxicities in various marine organisms. Craddock (1977) has done a similar summarization for various types of oils and oil mixtures.

Marine organisms accumulate hydrocarbons either through direct ingestion of the oil or through transfer across membranes. Within the organism, the oil is either accumulated to toxic levels, metabolized, or depurated. The rate of hydrocarbon uptake is a function of the amount and type of the oil, the length of the exposure, and a combination of environmental parameters. An oil with a high aromatics content will pose a potentially greater impact than one with a low aromatics content.

Most of our present information on the effects of oil in cold waters has originated from the BLM/NOAA-sponsored program in the Alaskan Outer Continental Shelf. Much of this work has been summarized in Malins (1977). Additional data has been provided through various Canadian programs. Presently, the Canadians are conducting the Arctic Marine Oil Spill Program (AMOP) studies to determine the effects of oil spills in Arctic regions. Various studies were conducted in Swedish waters following the Tsesis spill in October 1977. The results of studies conducted during the first year following this spill have recently been summarized by Kineman et al. (1980).

Rice (1977) compared the sensitivities of cold-water fish and shrimp with those of similar species from warmer climates and found the cold-water species to be less resistant to oil. He speculated that this was due to a greater persistence of toxic aromatic compounds at the colder temperatures due to reduced rates of bio-degradation and evaporation.

In spite of the fact that temperature is a major influence on the physiology of aquatic organisms, few studies have been conducted on the effect of temperature on petroleum accumulation by these organisms. Harris et al. (1977), however, observed that the copepod *Calanus helgolandicus* retained 44% more naphthalene when exposed at 6°C as opposed to 10°C. Fucik and Neff (1977) also observed that the uptake of naphthalenes by temperate and boreal clam species was higher at the lowest exposure temperatures. However, when the clams were moved to clean water, temperature had no noticeable effect on the depuration of the hydrocarbons. Information obtained in these studies suggests that the observed patterns may be due to inherent physiological mechanisms rather than a slower rate of degradation of the oil at the lower temperatures.

For past oil spills, few impacts to pelagic organisms have been documented. This is probably due to a number of factors, including sampling difficulties. Most pelagic fish species can avoid the area of a spill while the time that other nektonic and planktonic species spent in the vicinity of a spill can be minimal due to water movements or other factors (for example, vertical migrations). Percy and Mullin (1975) found that most neritic invertebrates in arctic waters were relatively tolerant of high concentrations of dispersed oil.

The sediments are the final sink for most contaminants that enter the marine environment. Once oil reaches the sediments, it may remain for long periods of time. Therefore, the organisms that inhabit the sediments in an area where oil has been deposited are exposed to a potentially chronic source of hydrocarbons. This is potentially one of the most significant impacts of an oil spill. Biological recovery in such an area can take many years. Most of the effects from such cases have been studied in easily accessible nearshore or intertidal areas (for example, the *Metula* spill [Straughan 1978], the Amoco Cadiz spill [Conan et al., 1978], etc.). This is undoubtedly due to the ease of sampling these areas as opposed to the deeper, offshore waters.

SECTION 4

OIL SPILL BEHAVIOR IN COLD REGIONS

The most important environmental conditions that determine the behavior of cold-region oil spills are freezing temperatures, ice in its many forms, and snow. A description of the cold-region environments is provided, followed by a summary of the information presently available on the oil spill behavior, the vulnerability of the environment, and persistence of oil, with suggestions for oil containment and removal.

AQUATIC

In cold waters, the presence and nature of the ice cover is often the most important factor determining the spill behavior. Ice can be mushy or hard, smooth or irregular, consolidated or broken, and each condition results in a different oil behavior. A classification scheme (Michel, 1971) for the various common types of ice formations is illustrated in Figure 7 . There are three important ice types that have different influences on oil spill behavior and response. These are shorefast ice, fractured/deformed ice, and ice floes.

Oil spilled on or under shorefast ice is often the simplest situation for response. If the ice is of sufficient strength, heavy equipment and recovery crews can approach the oil from the shore. Oil spill response in fractured or deformed ice is more difficult since oil can be concentrated in leads, rafted ice, or piled ice, and the logistics of getting equipment and manpower to these oil pools can be a problem. The most difficult cold-region spill to respond to is an oil spill in moving ice floes. In this situation, few recovery techniques are available, and the hazards created by the moving ice may make response and cleanup very difficult.

Local ice properties also affect the spill behavior and response for each of these three ice conditions. These properties include ice salinity and porosity, ice strength, and extent of snow cover. In the following pages, these properties will be described and a discussion of oil spill behavior for the three ice conditions and optimum spill response techniques will follow. A familiarity with these sections will provide the OSC with information on containment and recovery strategies, oil persistence, oil distribution, potential ecological effects, and safety considerations for the cleanup crews.

Ice Porosity

As ice warms up and decays, its porosity increases, greatly affecting the penetration depth of the oil. The porosity increases less in freshwater ice

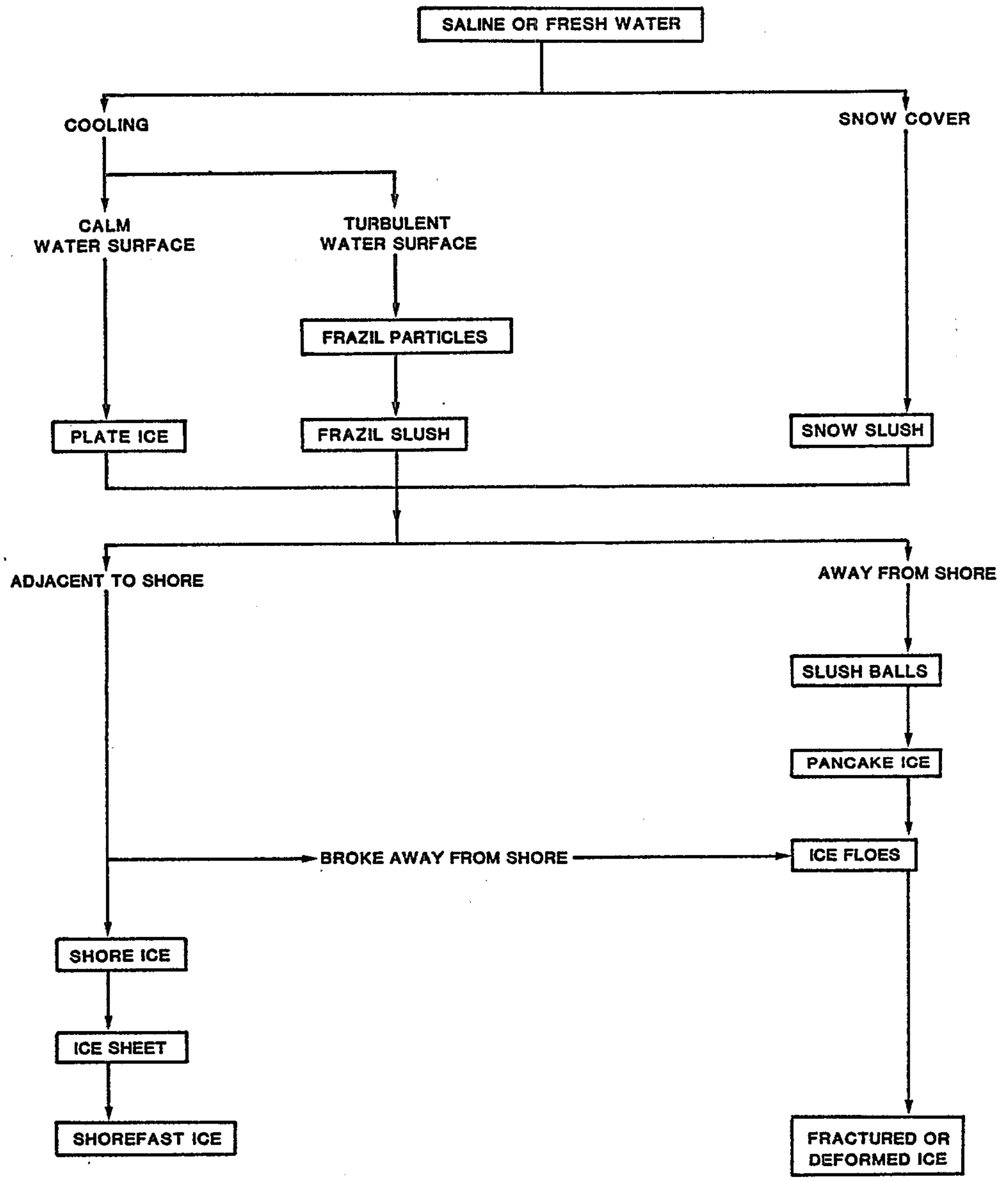


Figure 7 . Ice formation (Michel, 1971).

than in sea ice, because of the salt content of the latter. Therefore, oil spilled on or under freshwater ice will not penetrate as deeply as it would in sea ice.

The porosity of first-year sea ice varies greatly over the growing season. While it is growing, the ice has a low porosity, probably less than 0.1% of its total volume. As the ice warms up, the overall porosity rises to a value of about 1% of the total ice volume (NORCOR 1975; Martin 1977). The increase in porosity is due to the growth of large numbers of brine channels within the ice. The maximum oil concentration, in a 1.2-m^2 (12.9 ft^2) surface area for 1-m (3.3-ft) thick ice, is one barrel (159 liters = 42 gal) of oil, independent of the oil pooled on the ice surface.

The enlarged brine channels allow oil spilled during the spring to migrate down into, or up through, the ice. The brine channels also permit oil, trapped within the ice during the winter growth, to migrate to the surface where it is accessible for recovery. If an under-ice spill occurs during the decaying ice period, it will also surface, as illustrated by a field experiment at Balaena Bay, Northwest Territories (NORCOR, 1975). It was observed that oil spilled under 1.95-m (6.4-ft) thick ice rose to the surface in 50 min. The volume of oil within the cores taken at the site varied from 0.5 to 5%.

Therefore, as ice decays, oil easily penetrates and permeates the ice, be it seawater or freshwater, the penetration depth increasing with increase in ice porosity and decrease in oil viscosity. In a field test using Prudhoe Bay crude oil conducted by the U.S. Coast Guard (Glaeser, 1971), a porous ice surface, consisting of a layer of recrystallized ice approximately 5 cm (2 in) thick, was found to absorb oil up to 25% of its volume. In comparison, at Buzzards Bay the less viscous No. 2 fuel oil penetrated approximately 5 cm (2 in) into nonporous and less saline ice with a volumetric concentration of no more than 5% (Deslauriers et al., 1977).

No practical recovery technique exists for oil that has penetrated ice. Gathering contaminated ice and melting it down to remove the oil from the ice has been tried (Jerbo, 1973; Monsma et al., 1975). However, the small quantity of oil that can be recovered often does not justify the cost and time required for such an effort. Ice removal and cleaning techniques are discussed in Section 7.

Ice Strength

Response operations often require that men and equipment be on the ice. The safety of the ice as a work platform is measured in terms of bearing strength. Ice salinity, temperature, and cracks within the ice all affect the ice sheet bearing strength. Usually, the more saline the ice, the weaker it will be, except at temperatures below -20°C (-4°F). For temperatures above -20°C (-4°F), the maximum possible strength of sea ice is one-third the strength of freshwater ice (Assur, 1960). Figure 8 shows the freshwater ice-bearing capacity with the equipment weights used for spill response on shorefast ice.

The formation or cracks in ice will decrease the ice-bearing strength. If cracks are parallel to travel, the load on the ice should be reduced by 50%

(Figure 8). A reduction in load by 75% is recommended if cracks are both parallel and perpendicular to travel. In addition to cracks, areas of thin ice may exist where the ice appears to be thick and safe. These thin areas are formed by leads (open water areas in ice) that refreeze. Refrozen leads can be a serious problem, particularly if heavy equipment is being used. Therefore, ice thickness should be monitored by drilling or electronic detectors.

The ice temperature will also greatly influence the ice-bearing strength. From research on the antarctic pack sea ice, ice surface temperatures were divided into four categories or thermal periods (Table 9) (Vaudrey and Katona, 1975). The table shows that flexural ice strength is considerably reduced at the higher temperatures. Table 10 presents the minimum allowable ice sheet thickness for various vehicles and the four thermal periods. The safety factor used in these calculations was 1.5, so that in each category, ice failure occurs at a 50% increase in vehicle weight.

Snow has a significant impact on both oil-spill behavior and spill response efforts. At the Buzzards Bay oil spill, the accumulation of 12-cm (4.7-in) snow onto spilled oil that was in deformed and fractured ice greatly hindered the cleanup attempts (Deslauriers et al., 1977). Surveillance was hampered because the oil on the ice surface was covered by the snow, making it invisible from the air. In addition, an oil/snow mulch, consisting of 70 to 80% snow, was formed, making recovery, storage, and disposal difficult. The

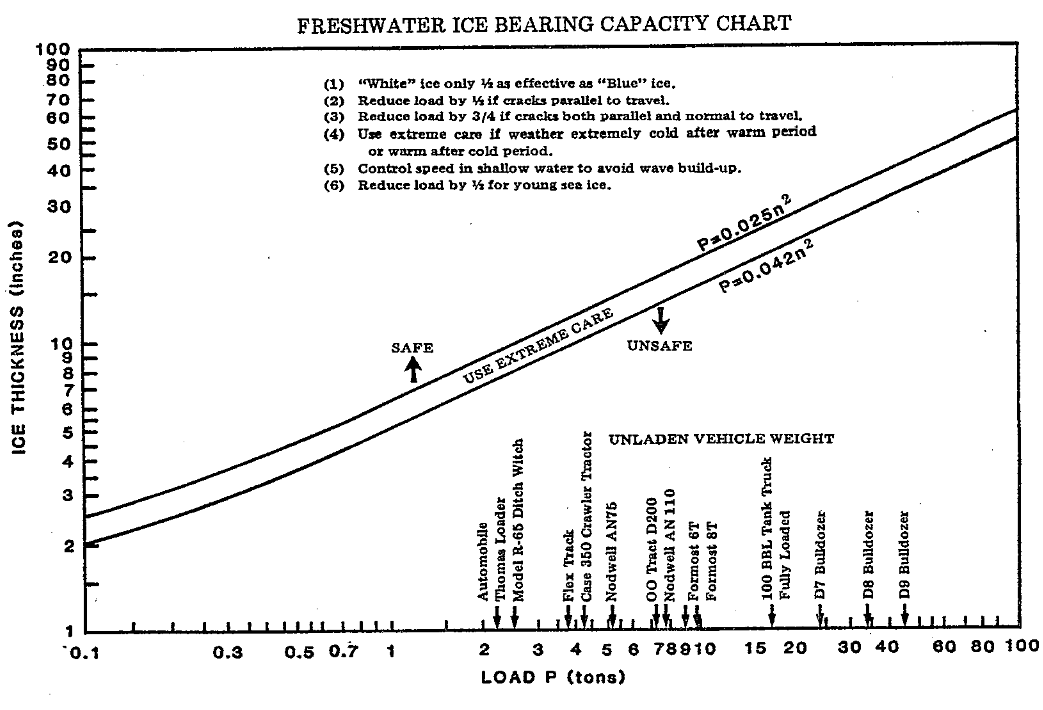


Figure 8. Freshwater ice-bearing capacity chart (Quam, 1978).

TABLE 9. ANNUAL SEA ICE SHEET MECHANICAL PROPERTIES
(Vaudrey and Katona, 1975)

Thermal period	Ice sheet surface temperature (°C)	Flexural strength (kN/m^2)	(psi)
1	-20 to -10	480	69.6
2	-10 to - 5	430	62.4
3	- 5 to - 3	400	58.0
4	- 3 to - 2	275	39.9

TABLE 10. MINIMUM ALLOWABLE SEA ICE THICKNESSES FOR REPRESENTATIVE EQUIPMENT AND VEHICLES (Vaudrey and Katona, 1975)

	Minimum allowable ice thickness (cm)(=.39 in)			
Vehicle	Thermal Period 1	Thermal Period 2	Thermal Period 3	Thermal Period 4
1. Pickup - Dodge W300 (GVW = 40.0 kN)	28	33	43	53
2. Pers. Carrier - Rodwell (GVW = 122.5 kN)	43	54	71	86
3. Pers. Carrier - Track-master (33.5 kN)	26	31	41	51
4. Caterpillar D-4 (76.5 kN)	51	61	79	97
5. Caterpillar D-8 (300.5 kN)	109	122	152	180
6. Caterpillar 950 (110.8 kN)	61	71	89	107
7. Caterpillar 955 (134.4 kN)	74	84	107	127
8. Road grader - Caterpillar 12F (125.9 kN)	66	74	94	112
9. Crane, wheeled-Pettibone 70 (314.6 kN)	102	114	145	175

interaction of oil and snow is possible for all exposed spills in cold regions and will be discussed later in this section.

Shorefast Ice

Oil spilled on top of or underneath solid shorefast ice requires certain containment and recovery techniques, which are determined by the oil behavior. This behavior depends on the oil properties, ice salinity, under-ice currents, and whether the ice is growing or decaying. Oil spilled under or on solid ice has been the subject of intensive study. In the following pages, the information on oil and shorefast ice is divided into three topics: oil spreading on or under ice, oil behavior in growing shorefast ice, and oil interaction with decaying shorefast ice.

Oil Spreading on or Under Shorefast Ice--

The spread of oil on or under ice is determined by the ambient temperature; the ice surface slope, roughness, and porosity; the oil properties; and, to a certain extent, wind velocity and water currents. For the basic case of oil spreading in still water under smooth, nonporous ice, experiments by Chen and Scott (1975) and Keevil and Ramseier (1975) reveal that crude oil gathers in layers that are 10-15 mm (.39-.59 in) thick. Equations have been derived for the calculation of the oil spreading rate on or underneath an ice cover (McMinn, 1972; Hoult, 1975; Chen et al., 1974). From a practical standpoint, the oil in any given spill likely will have spread to its maximum area before the initiation of any response action.

The maximum area of a spill on or under shorefast ice is determined primarily by the roughness and porosity of the ice surface. In addition, external forces such as wind for spills on the ice and water and currents for spills under the ice, also influence the areal spread. A description of the influence of ice surface roughness, ice porosity, wind, and water currents on oil spreading on and under shorefast ice follows.

Ice generally has a rough surface caused by its initial growth from frazil crystals, deformation by winds and currents, flooding and refreezing of the ice, lifting and dropping of the ice cover by tidal action, and variations in the distribution of the insulating snow cover. These conditions create many undulations and cavities in the ice. When oil is spilled on or under the ice, it spreads from the spill source, filling one undulation after another. This process has been observed in experiments conducted by Hoult (1975), NORCOR (1975), Adams (1975), and Glaeser and Vance (1971).

Oil may pool in ice undulations and cavities, greatly aiding recovery. Unfortunately, the under-ice undulations and cavities are difficult to locate. The presence of under-ice undulations may be indicated by snow drifts (Martin, 1978). Snow drifts that form a hard, crusty surface do not migrate and make very good insulators. Thus they play an important role in limiting the ice growth in that area, creating an under-ice undulation. Therefore, if a spill occurs under the ice with hard snow drifts present, pools of oil may be concentrated below the snow drifts. Another way to locate under-ice undulations is by using an ice thickness sensor. Geophysical Survey Systems, Inc. has developed a VHF impulse radar that can profile ice thickness and irregularities;

it can be used from aircraft or on the ice (see Section 6).

It has been observed in the Canadian Arctic (NORCOR, 1975) that under-ice irregularities tended to be sinusoidal and of a depth approximately equal to 15% to 20% of the mean ice thickness. Kovacs (1977), in a study of ice thickness profiling near Prudhoe Bay, estimated that the under-ice roughness would limit the areal coverage of one barrel (159 ℓ = 42 gal) of oil to 5.9 m^2 (63.5 ft^2) in ice 2 m (6.6 ft) thick. It should be noted that this number is based on a limited amount of data. The under-ice roughness is normally greater than the surface roughness; therefore, the ultimate area of spread on top of ice without snow cover could be expected to be larger than under the ice, assuming the same ice porosity and neglecting the effects of winds and currents (Hoult, 1975).

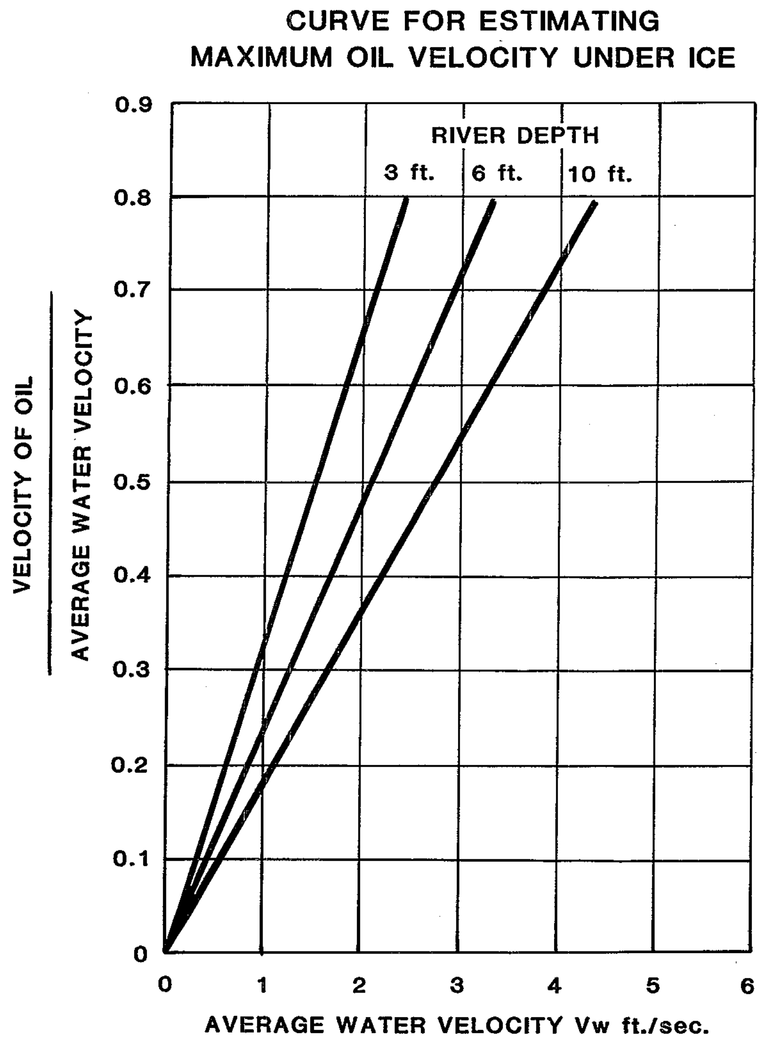
Aside from the ice-pocket filling process, the absorption of oil by the ice surface limits the areal distribution of the oil. In ice with a porous crystal structure, light-viscosity oils freely penetrate the ice, while more viscous oils do not penetrate as easily. Ice porosity will become greater during thaw and will also increase in salinity.

In addition to these spreading mechanisms, high winds can also transport oil on top of ice. In a spill at Deception Bay (Ramseier et al., 1973) and at Buzzards Bay (Deslauriers et al., 1977), oil that was initially concentrated in pools on the ice surface was blown out onto the ice in thin layers. This wind-spreading of the oil greatly increases the rate of evaporation but makes recovery more difficult.

Under the ice, water currents help to spread spilled oil. A minimum current velocity is needed to initiate the movement of an oil slick. For the simplest case of smooth ice, this minimum current for No. 2 oil has been observed to be about 3.5 cm/s (1.38 in/s), while for more viscous crude oil, the minimum current was substantially higher, 10 cm/s (3.94 in/s) (Uzuner and Weiskopf, 1975). Therefore, if a slick is to be transported underneath an ice cover, the water velocity must exceed these values. Once movement is initiated, the slick transport is a function of water velocity and depth as shown in Figure 9 (Quam, 1978). These measurements were taken under river ice with wave-like undulations and may not be reliable for different ice surfaces. Neither Uzuner and Weiskopf (1975) nor Quam (1978) noted oil adherence to the ice, and the ice had an oil-free surface once the oil had passed.

Oil moving on or under the ice can be contained using any of several techniques. For oil containment on the ice surface, berms could be made of snow or ice (see Section 7), or sorbent booms (see Section 7) could be used. For oil moving under shorefast ice, ice slots cut at a 30° angle to the water flow would contain oil and also allow access to the oil for recovery. Ice barriers, such as ridges and keels, provide collection points. Other methods include cutting through the ice and installing a conventional open-water boom or, if water currents are low and oil volume high, installing a deep-skirted boom.

Recovery techniques for oil slicks on the ice surface include use of sorbent material (see Section 7). The employment of motorized graders may be



Note: The velocity at which oil will travel under ice is dependent upon the water velocity and the average depth of water below the ice. These measurements were taken under river ice, with wave-like undulations, and may not be reliable for different ice surfaces.

Figure 9. Maximum oil velocity under ice (Quam, 1978).

practical for large spills. For oil pools on the ice surface, either in-situ burning or direct suction provide a fast response. No easy methods exist for recovering oil under the ice. Access to the oil would first require methods such as ice slotting or drilling through the ice (see Section 8). The use of an oil mop oleophilic rope (see Section 8) may be useful for under-ice spills when put through two holes in the ice. Once the oil is exposed in a relatively ice-free area, direct suction, conventional mechanical open-water devices, or in-situ burning can be used.

Oil in Growing Shorefast Ice--

Ice growth can incorporate oil, either spilled on top or underneath the ice. When oil is spilled under a solid ice sheet, the ice will grow both around and beneath the spilled oil. If the air temperature is below freezing, a lip of ice forms around the edge of the under-ice oil lens within a few hours after the oil comes in contact with the ice. During cold periods, new ice grows beneath the oil within a few days (Martin, 1977; Keevil and Ramseier, 1975; Hoult, 1975; Adams, 1975; Uzuner and Weiskopf, 1975). The oil remains trapped underneath the ice until the ice warms and brine channels open.

Oil on the ice surface can also be entrapped by growing ice. In tests conducted with oil spilled in calm open water under ice-forming conditions, an ice layer formed beneath the oil (Scott and Chatterjee, 1975). If snow falls, the oil on top of the ice can be covered. Then, the absorption of solar radiation by the oil under the snow can cause melting and collapse of the snow. The melted snow later refreezes from heat loss either to the atmosphere or to underlying ice into an ice layer on top of (Deslauriers et al., 1977) or underneath (Martin, 1977) the oil. Therefore, the melting and refreezing of snow can form an ice/oil/ice layer that will affect cleanup.

It can be concluded that when oil is spilled in growing ice conditions, it nearly always will be encapsulated in the ice. Therefore, if spill response occurs during ice-forming conditions, it should occur shortly after the spill. Otherwise, recovery crews will be faced with a more difficult recovery situation. One possible technique is to drill to the oil lens and use direct suction (see Section 7) to recover the oil. If the oil can be located and is pumpable, suction may prove to be a good means of recovering oil with very little water content. If oil is entrapped within the ice, it may be best to wait for the ice to decay. When the ice decays, the oil rises through the brine channels to the surface.

Oil Interaction With Decaying Shorefast Ice--

During spring thaw, the decaying shorefast ice increases in porosity and decreases in strength. The increase in ice porosity is greater for sea ice because of the salt in the ice that leads to brine channel growth, as described in this section. Brine channels allow oil to rise through the ice to the surface. Therefore, oil spilled under the ice or sandwiched between ice will rise through and collect on the surface of decaying, porous ice.

Once the oil is on top of the ice, even under snow, the oil causes an increased absorption of solar radiation, hastening ice melting. A comparison of typical solar albedo (ratio of the solar energy reflected from a surface to the total solar energy incident upon the surface) values is presented in Table 11. Glaeser (1971) reports that oiled ice melted approximately 2 cm (0.8 in) more per day than clean ice. In Balaena Bay (NORCOR, 1975), oil reaching the surface of the ice led to the formation of oiled melt ponds. The ice sheet then rapidly deteriorated. This study concluded that, depending upon the nature and location of the ice sheet, oiled areas are likely to be free of ice between 1 and 3 weeks earlier than unoiled areas.

Oil spilled beneath decaying ice or incorporated between ice layers will probably migrate to the surface before the ice breaks up; spill response can

TABLE 11. COMPARISONS OF SOLAR ALBEDO*

Albedo ratio	Type of surface
0.9	New snow
0.6	Clean ice
0.5	Oiled snow
0.1	Open water
0.1	Oil pool

* Source: Deslauriers and Schultz, 1976.

take place at this time. However, ice breakup is unpredictable and may be premature because of storms. Since oiled ice decays faster than the surrounding ice, cleanup crews should use caution when on the ice. As the accelerated ice melt continues, drainage pools will form where oil will concentrate, making recovery easier. Complete ice melt under these pools will result in some oil being drained from the pond and swept under the surrounding ice.

Few practical containment techniques exist for this type of spill behavior. The oil will naturally form its own containment pools. The oil could possibly be directed to large containment pools by digging shallow trenches on the ice surface. The most favorable recovery technique would be in-situ burning (see Section 7). If burning is not feasible, direct suction of the pooled oil could be used. Another technique for thinly oiled areas or high-viscosity oil is the application of sorbents.

Fractured/Deformed Ice

Oil behavior in ice-covered waters is strongly dependent on the movement and deformation of ice. Ice that is not attached to the shore or bottom responds to wind and water currents by moving and deforming, leading to the formation of rafts, pressure ridges, rubble fields, and leads (Figure 10). These irregularities in the ice tend to concentrate the oil and shelter it from further spreading. Therefore, oil-spill response efforts under these conditions should initially focus on the areas of these ice formations.

Spill response logistics may be hazardous if the ice is susceptible to motion. The use of ice-strengthened marine vessels may be required, with men travelling a short distance on the ice to the concentrated oil.

Rafted Ice

Rafted ice forms when a flat ice sheet is subject to a compressive stress, generated by a combination of current and wind forces. The ice breaks by buckling, rather than by crushing, which frequently results in segments of ice

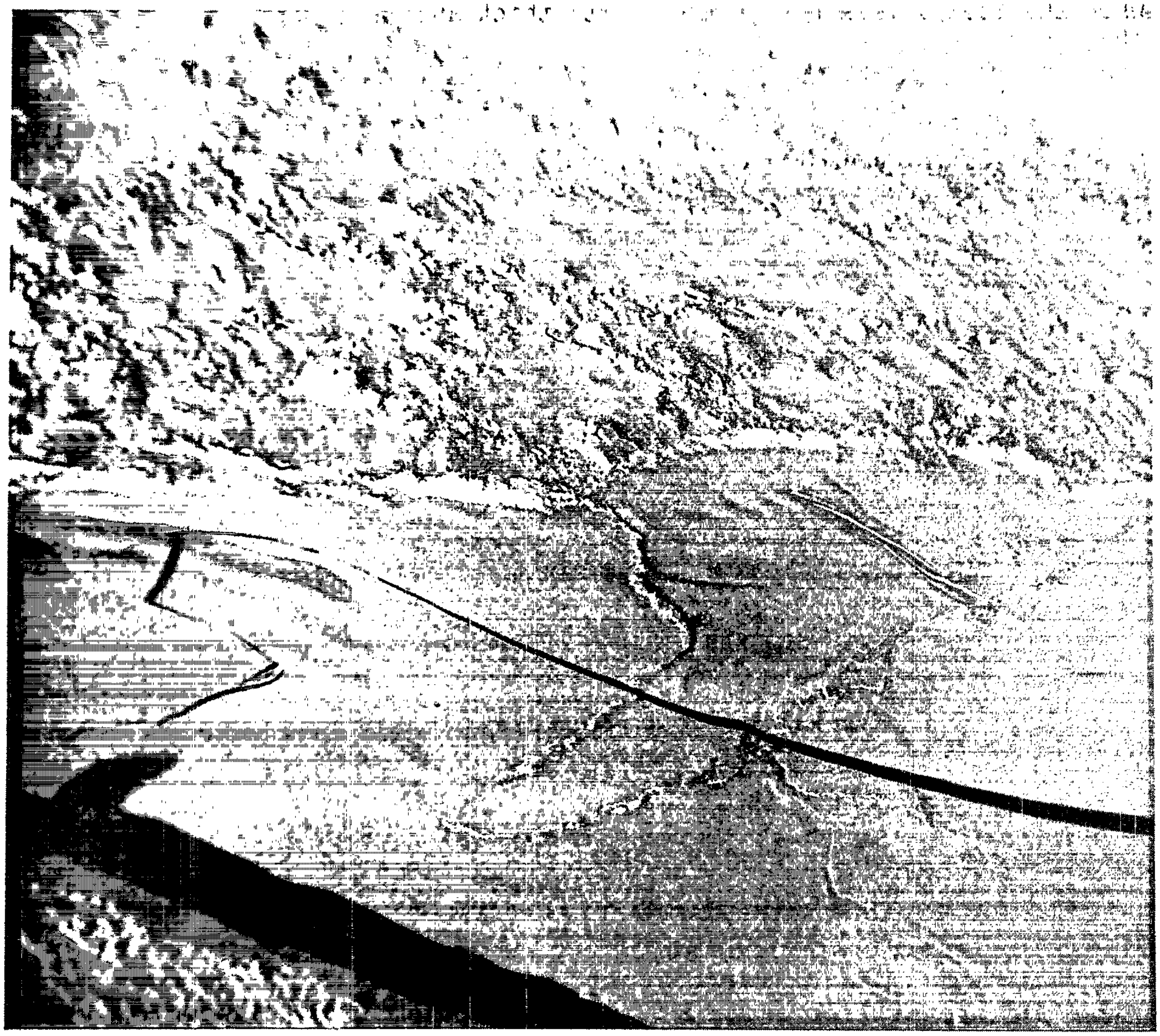


Figure 10. Aerial view of first-year ice.

The photograph was taken 60 miles west of Cape Lisburn, Alaska, in March 1978, by Seelye Martin. The aircraft was approximately 500 ft above the surface. Ice thickness was 1 m. There are two leads extending diagonally across the lower part of the figure. Pressure ridges and hummocked ice are in the upper part.

sheets sliding one over the other (Parmerter, 1974). This sliding occurs when the ice is less than 1 m (3.3 ft) thick and is elastic. The weight of the upper ice depresses the lower sheet to a point where sea ice will flow up over the lower sheet to form a wedge-shaped fluid layer.

Oil spilled on top or under rafted ice can replace the water in this wedge to form a contained oil pool. AT the Buzzards Bay spill, these rafted ice pools held approximately 30% of the oil spilled, and individual pools contained as much as 7.57 m^3 (2000 gal) of oil (Deslauriers, 1977). The sequence of sketches in Figure 11 shows an oil capture scenario as it occurred at Buzzards Bay.

The natural pools formed by rafted ice makes direct oil recovery possible. In-situ burning would be the preferred response. If this is not used, direct suction or sorbents (see Section 7) could be employed. If these oil pools are approached by marine vessels, caution should be used not to disrupt the natural containment of the rafted ice.

Piled Ice

Pressure ridges, rubble fields, ice jams, and hanging ice dams are each different forms of piled broken ice that can serve as additional accumulation sites for spilled oil. Pressure ridges and rubble fields occur in lake and sea ice, while ice jams and hanging ice dams occur in swift-moving rivers. Ice formation in each of these cases is different, but the oil/ice interactions are similar.

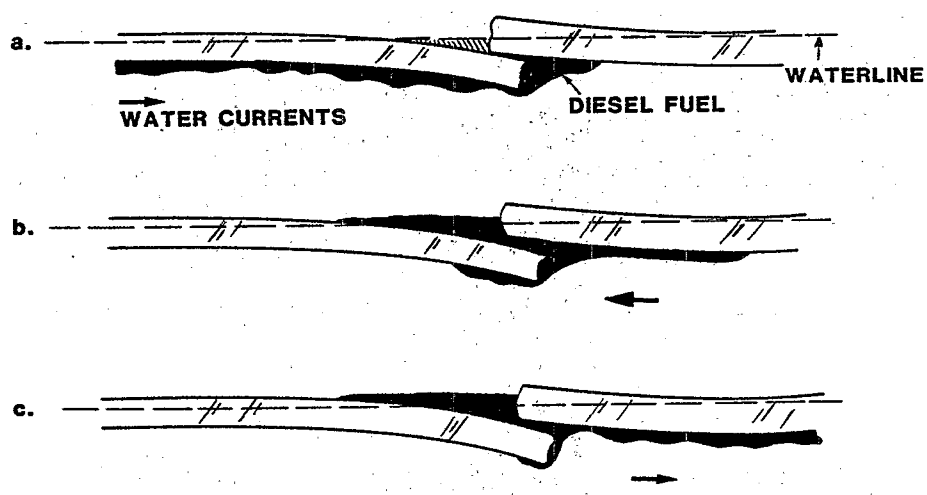


Figure 11. Flow of oil in rafted ice.

(a) oil flowing underneath the ice comes in contact with rafted ice;
(b) current reversal encourages oil filling into rafted ice pocket;
(c) reversal of current sweeps unsheltered oil away
(Deslauriers et al., 1977).

Pressure ridges and rubble fields form from forces exerted on the ice by wind, currents, waves, or moving ships that force the ice to pile. In piled ice, the ice sheet is broken into pieces, extending above and below the waterline. Figure 12 is an idealized sketch of the cross-section of a pressure ridge. The ice extending above the normal ice surface is called the sail, and the ice below is called the keel. Unlike a ridge with its clearly defined crest, a rubble field consists of randomly piled broken ice pieces. Weeks (1976) states that the ratio of sail height to keel depth is about 1 to 5, and that both ridges and rubble fields are in approximate hydrostatic equilibrium. When ridges first form, the blocks making up the ridge are separated from one another by air- and water-filled spaces called voids. Weeks (1976) states that from field observations, approximately 30% of the volume of a young pressure ridge is void space, making it very permeable to oil. After some time, and under proper conditions, these voids begin to freeze.

Hanging ice dams and ice jams are piled ice formations in rivers. Hanging ice dams occur when frazil ice or ice pieces accumulate underneath a stable ice cover at one point to form a dam. Ice jams occur when the ice is breaking up and ice floes pile up at one point, jamming further progress of the ice. Both of these ice formations have keels and void spaces.

Oil released either on or under the ice that comes in contact with these piled ice formations will be contained at the base of the sail or keel, flow into the void spaces, become trapped within it during its formation, or flow around or under it. Oil spilled under the ice can effectively be contained by the keel. In an experiment (NORCOR, 1975) where water currents were 10 cm/s (3.9 in/s), oil was spilled under ice in the vicinity of an old pressure ridge with few void spaces. The currents transported the oil at the base of the keel, so that the oil gathered in a pool adjacent to the pressure ridge. The oil remained there until the ice began to decay.

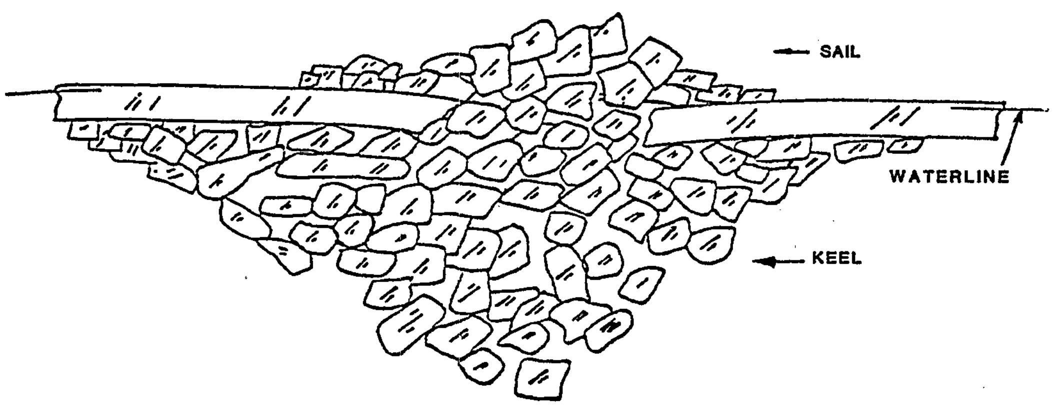


Figure 12. Pressure ridge cross-section (sketch).
(Deslauriers et al., 1977)

Oil can be trapped within piled ice during its formation. Contaminated ice pieces are compressed together, creating a pile of oiled ice, with some oil possibly pooled in the void spaces. Oil also can be trapped in a lead that is squeezed together into a pressure ridge or rubble field. Oil then is mixed within the broken ice and possibly spread on top or underneath the surrounding ice cover.

Oil can flow also into the void spaces of piled ice. At Buzzards Bay, oil spilled under the ice was contained by a newly formed porous rubble field (Deslaurier et al., 1977). Oil flowing under the ice hydrostatically filled the many cracks and appeared on the surface (Figure 13). Once in the rubble field, the oil was prevented from spreading further. The oil also pooled sufficiently in the rubble field so cleanup crews could recover the oil by direct suction.

Factors affecting the transport of oil under or around piled ice formations are the oil volume and type; the ice keel depth, slope, roughness, and width; and, most important, the current. Research is presently being conducted by Arctec, Inc., Columbia, Maryland, to investigate further how ice keels contain oil. Until these findings are complete, it is necessary to assume that an ice keel's ability to contain oil is similar to that of an oil boom. In general, a current velocity of about 51 cm/s (1 knot) normal to the boom can be considered the upper limit for successful retention of oil.

Cleanup crews should concentrate their efforts on the upcurrent side of the ice keels where oil is most likely to collect. Access to under-ice oil spills can be accomplished by ice-slotting techniques. Access holes can be made also by powered hand-held augers or large truck-mounted drills.

Once the oil is exposed, recovery methods (see Section 7) include in-situ burning, the use of sorbents, or the use of mechanical recovery skimmers. Oil pooled within the void spaces of the piled ice could be collected by drilling and direct transfer; however, recovery may not be practical if the ice pieces are piled high and close together.

Leads

When sheets of ice converge, they form rafts, pressure ridges, and rubble fields, as described in the previous pages. Conversely, when the sheets

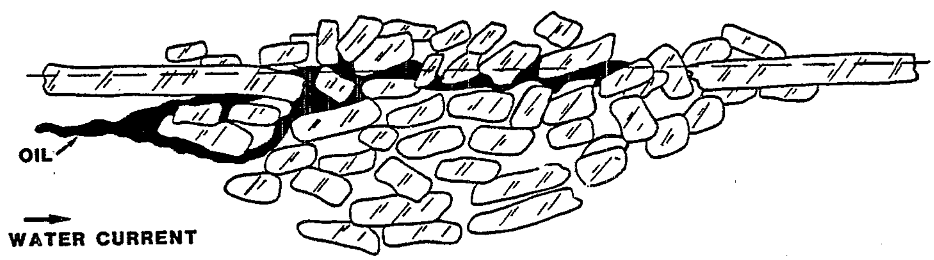


Figure 13. Oil flowing into a rubble field (idealized cross-section) (Deslauriers et al., 1977).

diverge, they leave long linear regions of open water called leads. These leads will open and close, depending upon wind stresses, water currents, and ship traffic. Birds, seals, polar bears, and walrus often gather in these open-water areas, making leads one of the most biologically vulnerable areas in ice-covered waters.

Oil spilled in a lead will come in contact with the surrounding ice edge. When a lead closes, the oil along the ice edge can be either contained, forced beneath the ice, dispersed in the water, or washed on top of the ice. Factors that determine the direction of oil movement include the forces (for example, waves and winds) pushing the oil against the ice, the specific gravity of the ice and oil, and the thickness of the ice edge.

The ice edge can serve as an effective containment mechanism. In several cold-region spills, the ice edge contained, or partly contained, the oil and served as an effective barrier against further spreading (Ramseier et al., 1973; NORCOR, 1974; Lamp'l, 1973). However, at the Buzzards Bay spill, the oil generally flowed under the ice edge of leads. The ice failed to contain the No. 2 oil because of wind and current stresses -- the water velocity was approximately 50 cm/s (1 knot) and the wind averaged 12 m/s (23.4 knots) (Deslauriers et al., 1977).

Spill-response efforts should, therefore, concentrate on the downwind ice edge of a lead where the oil is most likely to collect. Unfortunately, this natural containment system may fail if the winds or currents are too strong. These leads may close or open farther without warning, so precautions should be taken. Containment or concentration of the oil for recovery in leads may be accomplished by booms constructed for cold-region use (see Section 7). Use of booms, however, would appear to be practical only in very large leads.

Recovery techniques (see Section 7) must consider that broken ice pieces will probably be mixed with the oil. If oil is sufficiently concentrated along the lead edge, in-situ burning may be used. If mechanical recovery is necessary, the Lockheed disc or the Oil Mop rope could recover the oil with small ice pieces present.

Ice Floes

Response to an oil spill in ice floes will probably be the most difficult and hazardous cold-region operation. Ice floes are defined as any ice, floating freely on the water, that can move under the influence of winds and currents. Spill response becomes very complicated under these conditions, and even a large cleanup effort may yield negligible results.

The Buzzards Bay spill that occurred in fractured/deformed ice was initially confined to an area of 0.1 km^2 (25 acres) but after ice breakup, the oil spread in between floes covering a 19.4-km^2 (7.5-sq.mi.) area, making further cleanup impractical. Therefore, if oil is spilled in shorefast or fractured/deformed ice, all efforts should be concentrated on cleanup before the ice breaks into ice floes.

Oil behavior is determined by the oil properties and ice floe size, porosity, movement, and, most important, concentration. Low-viscosity oil has a tendency to penetrate into the ice and spread thinly on the open water between the floes. High-viscosity oil tends to adhere in a thick layer to the ice surface and concentrate between the ice floes. The floe size (varying from 1-m [3.3-ft] diameter pancakes to floes several kilometers [miles] in diameter) affects the oil spill movement, response logistics, and choice of cleanup technique (Figure 14). The ice porosity will depend on the salinity of the ice and on the ice growth/decay cycle and affects oil penetration into the ice. Ice movement will be approximately at the same speed and in the same direction as the water current, neglecting wind effects. Mobile ice floes move at about 3% of the wind velocity, and generally at an angle of 20° to 40° to the right of the predominant wind direction (Goddard Space Flight Center, 1974). The ice movement will greatly influence spill transport, particularly at the higher ice concentrations.

The most important factor influencing the spill behavior and response in ice floes is the ice concentration. Discussion of oil spill behavior can be divided according to ice floe concentration (realizing that there are variations in spill behavior resulting from differences in ice floe size), porosity, and movement. The ice floe concentration is divided into three ranges (1% to 20%, 20% to 80%, and 80% to 100%), corresponding to three different types of preferred spill responses.

Up to 20% Ice Floe Concentration--

Oil slick behavior on water covered by up to 20% ice floes is in many ways similar to that in open-water spills. Oil moves away from its source through the combined effects of spreading and drift. Oil does not usually spread in the form of a single slick of nearly constant thickness but rather in relatively thick slicks with diameters in the range of 0.5 to 10.0 m (1.6 to 32.8 ft) and a 5- to 10-mm (0.2- to 0.4-in) thickness (Milgram, 1978). These slicks may contain nearly 90% of the oil by volume, concentrated at the leading edge in an area about 1/8 of the total slick area (Jeffrey, 1973; Mackay, 1977). Generally, the oil in the thick slicks is removed in successful cleanup operations.

Coatings of oil may exist on some of the floes, but most of the oil will be transported by winds, waves, and currents. Slick transport by wind (wind velocity measured at 10 m from the water surface) varies from 1% to 5% of the wind speed. Usually a wind drift factor of 3% of the wind speed is used. Drift angles of 1° to 45° have been recorded when measuring the deflection of the slick to the right of the wind vector as a result of the Coriolis force. Usually a drift angle of 20° is used. A simplified method of predicting the slick movement is provided in Figure 15.

Cleanup response is feasible for oil spilled in ice floe concentrations of up to 20%. Equipment should be able to separate oil from broken ice, withstand impact from ice floes and also to be operated in below-freezing temperatures by personnel with heavy gloves. One of the most difficult problems is containment in moving water. Any attempt to restrict the movement of ice on moving water to contain or divert oil immediately results in two significant problems: stress on the boom and blockage of oil movement. However,

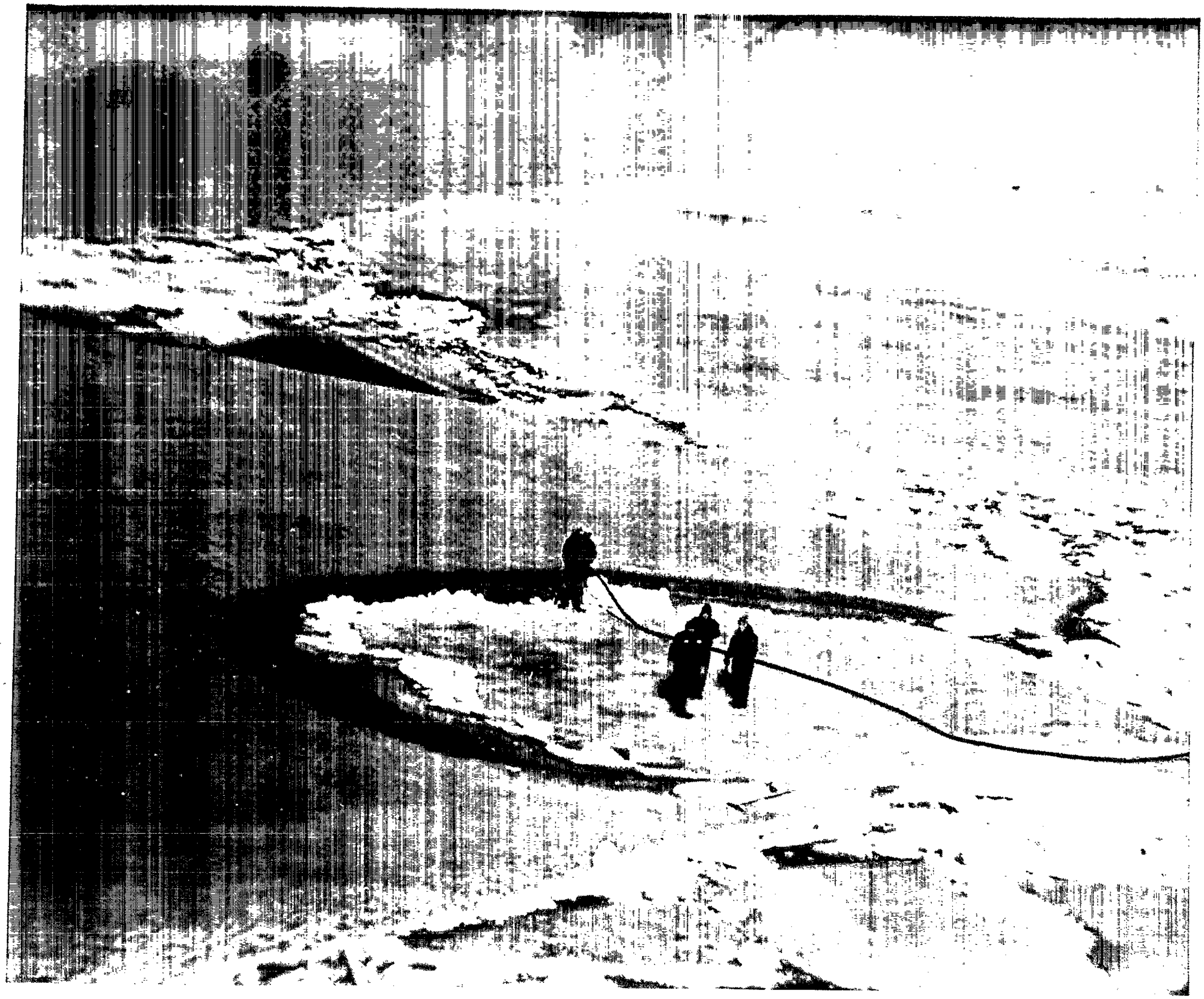
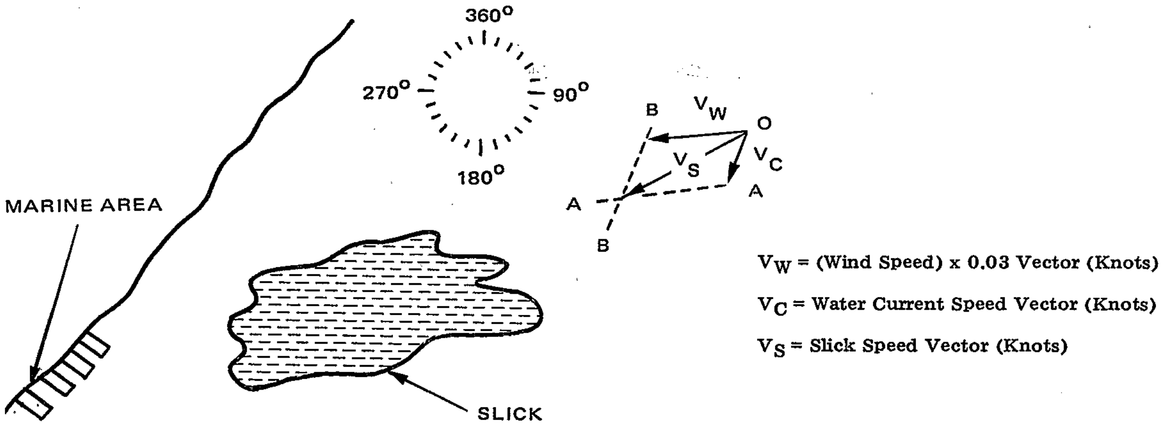


Figure 14. Suction hoses recovering oil around ice floes -- Buzzards Bay, January 1977.



Procedure:

1. Lay out 3% wind speed and current vectors from known headings. Use same scale (inches/knot) for both vector lengths.
2. Draw line parallel to V_W at the tip of V_C (A-A) and line parallel to V_C at the tip of V_W (B-B).
3. Draw line connecting intersection of AA, BB, and O. This is the slick speed vector, V_S.
4. Measure length of V_S in inches and determine knots from scale in Step 1.
5. With compass heading and speed of slick known, estimate time of arrival at sensitive areas; deploy men and equipment as required.

NOTE: 1 knot = approximately 1.7 ft/sec = 102 ft/min.

Figure 15. Prediction of slick movement (U.S. Navy, 1977)

conventional containment and cleanup devices could perform in these ice concentrations if water currents are not high.

Containment booms that meet the criteria discussed in Section 7 could be used. Marine vessels would be required to prevent large ice floes from entering the containment boom. If ice accumulation occurs in the boom, the boom should have the ability to ride up over the ice and let it pass. Oil/ice booms may have some application in river ice situations. Air bubble barriers could be useful in limited situations.

Recovery devices (see Section 7) would have to separate the oil and ice. Devices with this capability include the Oil Mop rope and the Lockheed disc. Dispersants may be practical if conditions are suitable for its use.

20% to 80% Ice Floe Concentration--

Spilled oil in ice concentrations from 20% to 80% is often the most difficult situation to respond to. Low-viscosity oil will penetrate into the ice (depending on the ice porosity) and flow between the ice to a thickness partially dependent upon the concentration of the ice field. Medium-viscosity oil will typically adhere to the ice surfaces and bleed oil sheen, or the lighter ends, into the surrounding waters. High-viscosity oil would have a far greater tendency to be contained by the broken ice, with resulting greater oil thickness. If there is enough interaction between the oil and ice, all of the heavy fractions of the spilled oil may adhere to the ice surfaces.

Oil that initially penetrates into the ice floes will probably be later released as a thin oil sheen. During the 1977 Buzzards Bay spill (Deslauriers et al., 1977), No. 2 fuel oil, incorporated in the relatively stable ice, was slowly released at breakup. As the ice floes deteriorated, oil that had penetrated into the ice streamed from the floes in the form of sheen. The oil was therefore allowed to travel a considerable distance with the ice before being released into the open water. During ice breakup, spill response operations were attempted with essentially no recovery. Contaminated ice floes that drifted into coves settled on the beaches and leaked the oil into the sediments and beach grasses.

Oil that adheres to ice floes would also be impractical to recover. In the 1977 Ethel H spill on the Hudson River (Morson and Deslauriers, 1977), No. 6 oil was spilled in a broken ice field. Before the spill, ice floes created from the breakup of the shorefast ice covered 80% of the river at some locations. As these ice floes traveled down the river, heavy tarry oil adhered to many of the ice floes. In some instances, the ice floe surface was 50% covered with oil. A thin sheen of oil was observed streaming from some of the more heavily oiled ice pieces. When the ice floes became more closely packed, the oil between the floes was contained to a greater thickness. Recovery operations in the moving broken ice were attempted, but no significant volume of oil was recovered.

Frazil and slush ice are often seen between ice floes, where the spilled oil will be concentrated, on open water, and under solid ice. Laboratory experiments conducted by Martin et al. (1976) revealed that slush and frazil ice have high porosities. It was concluded that because of the high porosity and warm surface temperature, oil spilled within slush ice probably behaves as if the slush ice were not present. Based on these tests, it appears that oil would have to be recovered with, or separated from, the frazil or slush ice it is floating on.

The only available containment technique for 20% to 80% ice concentration is the oil/ice boom (see Section 7), which would create an open-water area where conventional response equipment could be used. No recovery techniques are presently available for these ice floe concentrations.

80% to 100% Ice Floe Concentration--

Spill response in ice concentrations from 80% to 100% is difficult and hazardous. However, medium- and high-viscosity oils may be sufficiently concentrated by the tightly packed ice to allow in-situ burning.

Experiments (Vaudrey and Katona, 1975) on the dispersion of Prudhoe Bay crude oil and No. 2 diesel fuel, in a broken ice field of 95% concentration, showed the importance of oil viscosity. When the crude oil was poured into the broken ice field, it built up in thickness between the ice pieces instead of spreading. After 91 ℓ (24 gal) of crude oil were deposited, the slick covered an area of only 2.8 m^2 (30 ft^2). On temperature waters, the same volume would cover approximately 28 m^2 (300 ft^2). The oil thickness in the center was 9.5 cm (3.7 in), varying to about 6.4 cm (2.5 in) near the boundary. When No. 2 oil was spilled under the same conditions, it spread rapidly and thinly through the broken ice field.

If there are waves present in broken ice of high concentration, the ice field will periodically compress and expand so that the oil will be progressively pumped along channels. If a channel is restricted and the film is sufficiently thick, the oil will be forced onto the ice surface (Martin et al., 1976). Oil spilled under these conditions will be concentrated in the open water between the pancakes and along the edges of the ice pancake surface. The only response technique available for this broken ice condition is in-situ burning (see Section 7).

Oil Spill Trajectory Modeling in Cold Regions

In modeling of oil spill trajectories, surface ocean current and wind fields need to be specified (though uniform winds are usually used for the entire region). In regions without ice, trajectory modeling has been successful.

The presence of ice makes the problem much more complex. In the Beaufort Sea, for example, there are three dynamically changing regions where different processes act to trap and/or advect oil (Wadham, 1976):

Inner fast ice -- under this ice, oil tends to spread to equilibrium thickness.

Outer fast ice -- oil trapped by ridges and hummocks under the ice.

Shear zone -- oil partially trapped under the ice. With the formation of leads, oil becomes incorporated in pressure ridges. Oil is advected by moving ice with downstream lateral movement (Lewis, 1976).

Campbell and Martin (1973) and Lissauer and Tabeau (1980) reviewed the large-scale processes that act in the Beaufort Sea and indicate possible movement of 1 to 2000 km over a period of 2 to 3 months. Drifter trajectories are shown in Figure 16, which gives both references in full.

As oil comes to the surface of the ice, either by working its way through first-year ice (Lewis, 1976) or by pumping the formation of ice pancakes (Martin et al., 1976), the surface albedo of the ice is significantly lowered. Conceivably the lowering of the albedo could increase the surface absorption of solar energy and cause melting. Such interactions make predicting the fate of oil a complex process.

In regions of fast-moving currents, such as were observed during the Arrow oil spill (Task Force, 1970), the edge of an ice field can act as a barrier to oil flow, similar to a boom. However, if the current exceeds the critical velocity for the boom, oil will flow under the ice and be entrapped by

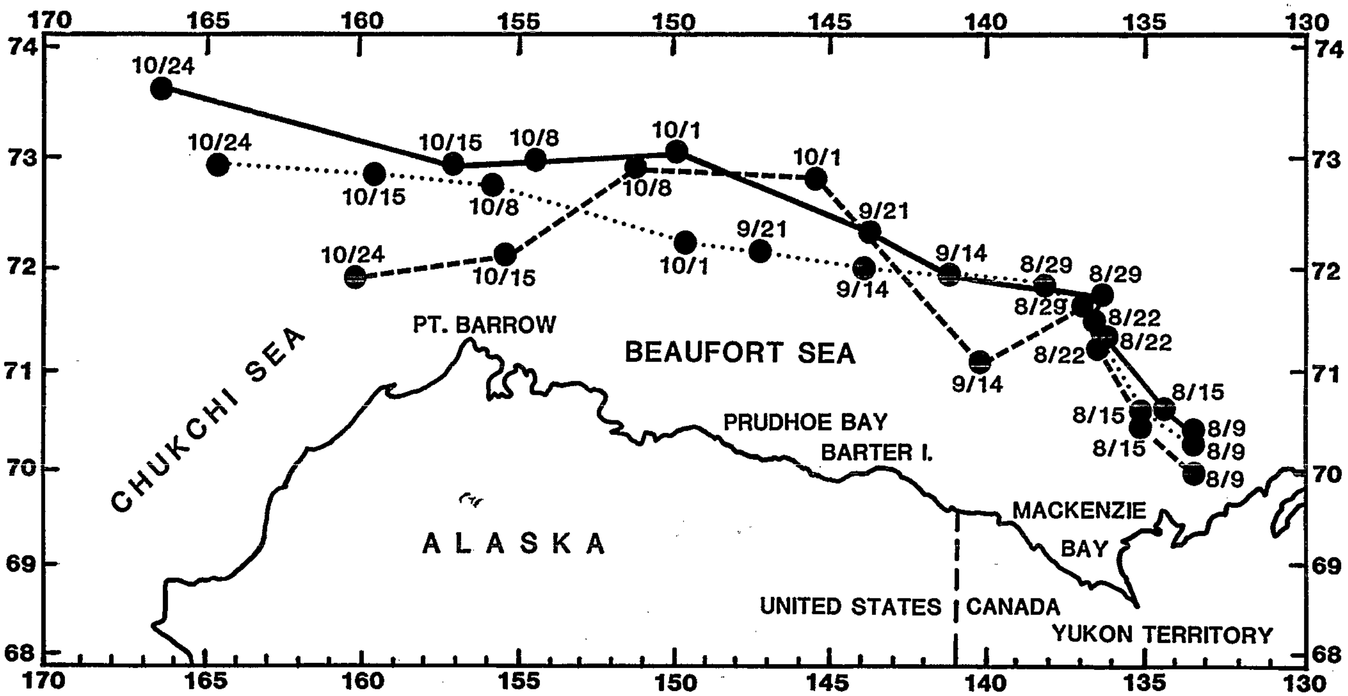


Figure 16. Deployment location and drift of satellite-tracked buoys released on August 9, 1979.*

* Lissauer, F.M. and P.A. Tabeau. 1980. Investigations to Determine the Transport of Oil in Arctic Waters, U.S. Coast Guard R&D Center, unpublished manuscript.

Campbell, W.J. and S. Martin, 1973. Oil and Ice in the Arctic Ocean: Possible Large-Scale Interactions. Science 181:56-58.

the uneven bottom surface of the ice. Oil then would be transported principally by the movement of the ice. Recent laboratory experiments have quantified some of the conditions that control the movement of oil under ice (Schultz and Cox, 1979). Other studies have shown that the underside of sea ice has an enormous capacity for containing oil (Kovacs, 1979). Martin (1981) discusses anticipated interactions between oil and ice in the Bering Sea.

Research efforts currently underway are making advances in our understanding of oil-ice interactions. However, reliable techniques for predicting the location of oil spilled near or under ice will not be available for at least several years.

COASTAL

Coastal environments vary significantly in response to a wide range of ice, wave, tide, wind, and sediment conditions. Understanding the roles that each of these conditions plays will provide insights into the spill behavior and proper response for each coastal environment discussed.

It is important to first discuss the conditions that determine oil spill behavior within various coastal environments. Much of this information has been gathered from publications by Owens (1971, 1977a, 1977b). Then the different coastal environments, their vulnerability to spilled oil, and the types of cleanup procedures best suited to each environment are discussed. A large part of this information is from publications by Hayes, Gundlach, and associates (Gundlach and Hayes, 1977; Gundlach et al., 1977, 1978; Gundlach et al., unpublished manuscript; Hayes and Gundlach, 1975; Hayes et al., 1976).

On-Shore Oil Distribution Parameters

Distribution and persistence of spilled oil on shores in cold regions is controlled primarily by ice, waves, tides, sedimentary characteristics, oil quantity, winds, and offshore transport. These parameters can vary significantly within different coastal environments, determine if the oil is readily buried, penetrates into the sediment, is swept off the shore, or is stored within some coastal environment.

Ice--

The formation of ice on the shoreline modifies littoral processes. Most important, ice can prevent or restrict spilled oil from reaching the shore or penetrating into the sediment. Ice can be present on the shore as shorefast ice, ice feet, or frost between sediments.

Shorefast ice extends as a solid sheet from the shore to a point bounded by open water or free-floating ice. Shore contamination is very unlikely if shorefast ice exists. The ice normally serves as an effective containment mechanism, preventing oil from spreading to shore.

Two past spills illustrate the effectiveness of shorefast ice in protection of the coast. In the 1977 Hudson River oil spill (Morson and Deslauriers, 1977), No. 6 fuel oil accumulated on the shores exposed to open water. In areas where shorefast ice existed, no oil was observed underneath the shorefast ice. However, at the Buzzards Bay oil spill (Deslauriers et al., 1977), No. 2 oil was observed to flow under the edge of the shorefast ice. There the ice failed to contain the oil because of wind and current stresses (water velocity was approximately 50 cm/s (1 knot) and wind averaged 12 m/s (24 knot). However, negligible shore contamination resulted because of the low water velocities in the shallower waters adjacent to the shoreline. Only a light oil sheen was observed flowing under the shorefast ice in the protected coves and bays. Based on these observations, it is concluded that if shorefast ice exists, the littoral zone probably will be protected, and coastal cleanup efforts should be directed to areas where shorefast ice does not exist.

The ice foot is a narrow fringe of ice attached to the coast, unmoved by tides, and remaining after the shorefast ice has moved away. Oil that has been deposited on an ice foot can be eroded if the adjacent water areas are ice-free, or the oil could be enclosed and buried by further accumulations of ice that would result from snow or from the freezing of wave spray and swash. Upon subsequent exposure, this oil would be released either into the sea or onto the shoreline.

When the beach is free of ice, individual ice floes can be pushed into the littoral zone by wind action. If the ice grounds on the beach, it can push sediment landward to form a sediment ridge. This movement mixes the oil with beach sediment or buries oil beneath the ice-pushed ridge.

On beaches in cold regions, water between sediments freezes during periods of sub-zero temperatures. This subsurface ice fills the spaces between the sediment particles and acts as a lower limit for oil penetration. A possible spill containment technique would be to spray water on a beach before oil reaches the shoreline (see Section 7). However, temperatures would have to be below freezing and the beach would have to be prepared well in advance of an approaching oil slick.

Waves--

Wave energy is important in dispersing, mixing, and burying oil. The levels of wave energy depend on duration, fetch, and wind stress. Coasts open to swell and/or storm waves are high-energy environments. Environments that are sheltered, or have limited waves, have lower energy levels. The transfer of energy to the littoral zone has a direct effect on oil. Mechanical energy from breaking waves causes the physical dispersion and speeds chemical breakdown of oil on the water and on the shoreline. In addition to the breaking up of an oil slick into smaller slicks or individual oil particles, mixing of oil and water can lead to the formation of emulsions, such as "chocolate mousse." Also, as waves break on a shoreline, oil can be splashed in the same manner as wave spray splashes beyond the normal high-tide swashline.

The most important effect of the energy transfer associated with wave action is the dispersal and redistribution of sediments. On a shoreline that has a large seasonal difference in wave energy levels, erosion predominates in one season and construction (or accretion) in another. Usually referred to as a summer/winter beach cycle, with erosion predominating in winter months, an example is commonly seen on the West Coast of North America. In other areas, such as on the Northeast Coast of North America, a storm/post-storm cycle predominates. In this situation, the seasonal variations are overshadowed by higher frequency cycles of erosion, during the passage of storms, and construction, in the post-storm recovery period. During an erosion phase on a beach, sediments and oil would be removed and transported into the nearshore area. If oil is deposited on a beach immediately following the erosion phase but before recovery has commenced, the oil on the beach would be buried as constructive waves return sediment.

Waves that approach the beach at an angle cause the longshore movement of sediment by a process that is referred to as longshore or beach drift, resulting from the swash running up a beachface at an oblique angle and the backwash combing down the sediments. Material on the beach surface is in a continuous state of motion and is transported along shore. The resulting migrating rhythmic topography can erode and deposit oil, as shown in Figure 17.

In the event of very high levels of wave action or a rise in water level caused by storm surge, wave activity may extend over the highest parts of the beach system. This process is referred to as overwash. If overwash is taking place, oil may be washed over the beach into the dune system and likely into the backshore lagoon.

Tides--

Tides influence the aging and distribution of oil and also control the effects of wave energy on oil. The variation in water level resulting from tides is one of the most important controls on the distribution of wave energy on a shoreline. In low tidal environments, wave energy is transmitted to the shoreline in a small range of elevation. The effectiveness of wave action to erode decreases as tidal range increases, because wave energy is dissipated over an increasingly larger vertical section of shoreline (Hayes, 1975). Since wave energy is a primary factor in the physical breakdown and dispersion of stranded oil, the increase in tidal range reduces the effectiveness of waves to clean an oiled shoreline.

Tidal range varies during monthly and six-monthly cycles. This cycle, or spring (high) and neap (low) tidal ranges, is particularly noticeable in regions that have high tidal range. If oil is stranded on the higher parts of the shoreline at times of spring tides, it cannot be affected by waves until the next spring tide (unless there is an increase in wave height that allows waves to affect that part of the shoreline).

The range of tides has a significant effect on the nonmechanical degradation of oil. Oil adhering to the sediments near the low-water level is submerged during approximately 75% of the time for each tidal cycle, whereas oil near the high-water mark is exposed for 75% of the time. As a result of this differential exposure, oil in the upper intertidal zone is subject to higher rates of weathering than oil that is covered by water during most of the tidal cycle.

Tidal range is a critical element in the distribution of oil on the shoreline. As the range increases, oil can be distributed over a wider intertidal zone. If the range is low, oil is concentrated over a narrower vertical band, and, therefore, the concentration of the stranded oil is greater. If the range

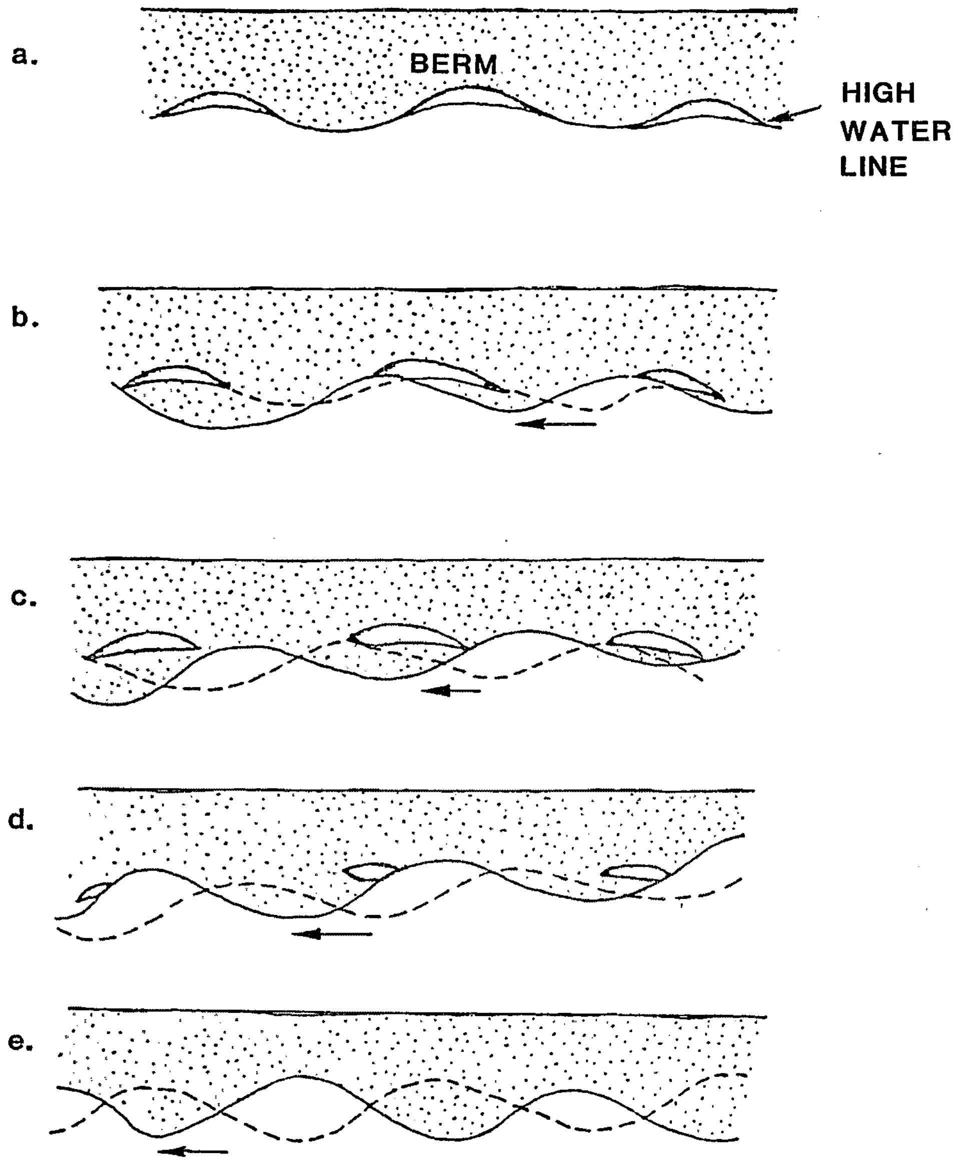


Figure 17. Oil deposits at high-water level -- plan view of migrating rhythmic topography (Owens, 1971).

is large, oil is spread over a wider surface area, and a layer of stranded oil, therefore, tends to be thinner.

Tidal currents can also play an important part in oil distribution. Erosion and deposition of sediments by tidal currents in the intertidal zone can cause burial or erosion of oil deposited there. Tidal currents in inlets or restricted channels lead to the transport, mixing, and breakup of oil on the water surface.

Sedimentary Characteristics--

The sedimentary characteristics of a spill-affected beach are also important considerations in oil-spill behavior. The grain size of the sediments affects the depth to which stranded oil can penetrate, though this also varies with the viscosity of the oil. Low-viscosity oils can permeate all except the finest grained sediments, such as compacted mud. For fine-grain sediment, the spaces between the particles are extremely small and are usually filled with water. High-viscosity oils do not usually penetrate sand more than a few centimeters, except where high air temperatures reduce oil viscosity or when the oil has been on the beach for some time. If the sand is saturated with water, or the spaces between the particles are frozen, oil will not penetrate beyond the surface.

On well-sorted pebble or cobble beaches, where the spaces between the particles are not filled with smaller sized sediments, even the semi-solid and tarry oils can penetrate the beaches. This occurred in Chedabucto Bay, where weathered Bunker C oil was observed to have penetrated as much as 1.5 m (4.9 ft) below the surface of a pebble/cobble beach (Owens, 1977a).

In general, for depositional beaches, the thickness of oiled sediment increases as grain size increases. At the Urquiola spill site in Spain (Figure 18) observations noted the depth of oil burial as a function of grain size, measured from most of the affected beaches in Spain. The emulsifying action of chemical agents enables oil to penetrate farther into the beach, making cleanup more difficult (Northeast Region Research and Development Program, 1969; Duerden, 1976). However, further research is necessary to document the actual increase in oil penetration that occurred as a result of dispersants on beaches of differing grain size.

Oil Quantity--

The quantity of oil spilled influences the possible total extent of affected shoreline, the distribution of oil on the beach, and the duration for which oil shoreline interactions (such as burial and mixing) can be maintained. Once oil impacts the shoreline, the quantity of oil determines its surface distribution on beaches. If there are low quantities of oil, oil is deposited primarily along the high-tide swashline. As the quantity increases, oil covers more of the beachface. Under heavier accumulation, the entire intertidal zone becomes covered with thicker concentrations, forming along the high tide swashline. Greater penetration into the sediment and deeper burial occurs with higher oil quantities.

Winds--

In addition to transporting oil slicks on water, winds can cause the

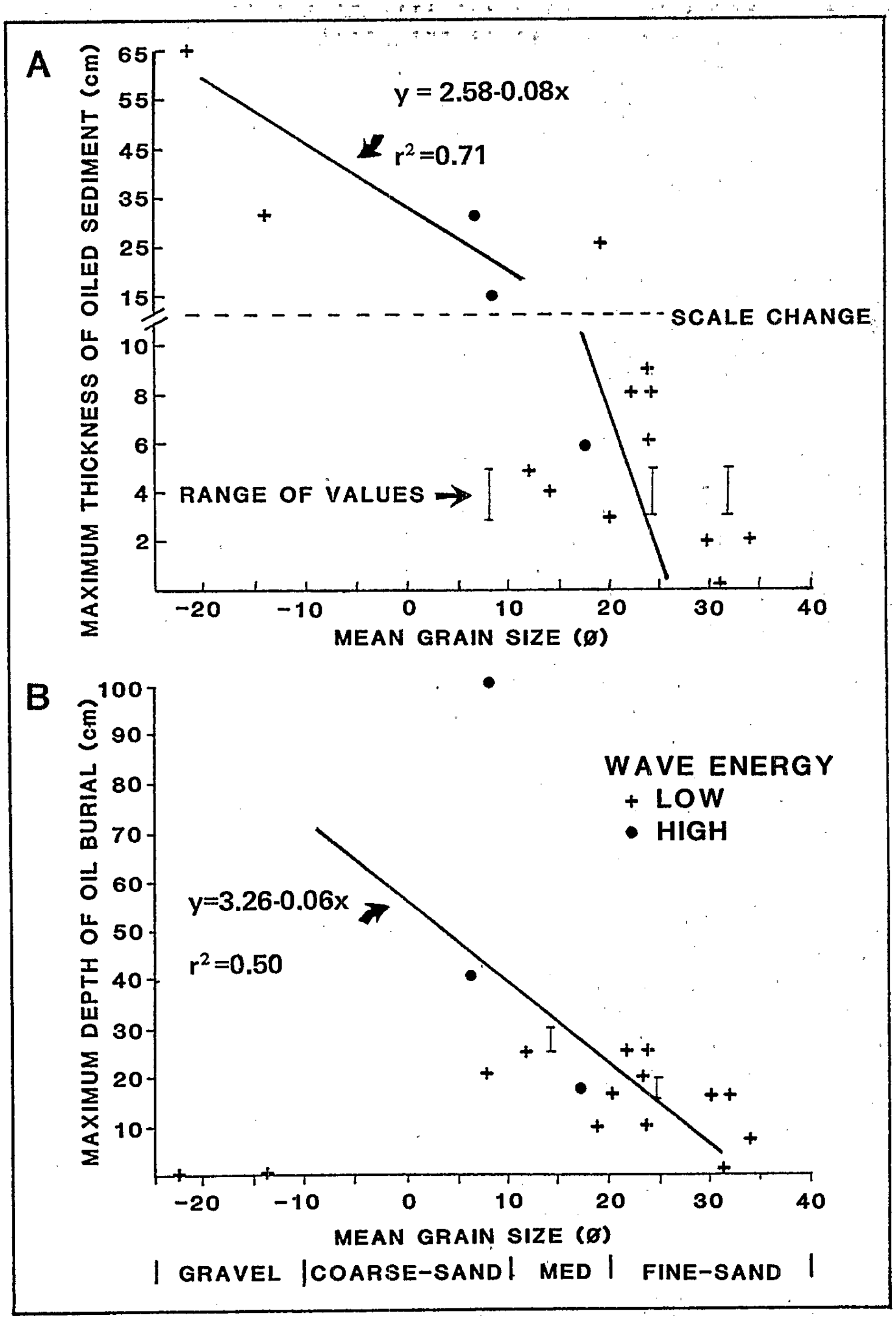


Figure 18. Depth of oil burial and thickness of oiled sediment as a function of grain size (Gundlach et al., 1978).

burial of oil by sediment or snow and affects the oil aging rate. Material that is sand-sized or smaller can be transported near the ground by wind. In an area where oil has been deposited, any transported sediment could bury the oil, which would be likely in a situation where the beach is backed by dunes and where the winds are offshore. During periods of storm winds, large volumes of sand can be transported, and an oil layer could be partially or completely buried within a few hours. The effect of such burial would be to reduce aging.

If loose snow is present, the wind can transport it over an area where oil has been deposited. Drifting snow can cover the oil in a very short time period. Also, as discussed before, the wind affects the aging rate by transporting volatized hydrocarbons.

Offshore Transport--

Offshore bottom pollution can come from oil that has impacted the shore. Mixing of oil and sediments on beaches and tidal flats forms a mixture that is denser than water. The manner in which oil is attracted to the sediment is important. If oil is unattached as tar balls, then the sediments may be cleaned easily by natural processes. However, if oil is directly attached to clay particles or organic detritus, then natural processes may only transfer the mixture to another site.

Once the oil adheres to the sediment, it forms a very stable mixture. In experimental work, tests were run to determine the uptake of different hydrocarbon species. Resuspensions of the oil-affected sediment, such as that which would occur in the natural environment, succeeded in removing only 15% of the oil, thus indicating a stable association. However, biological activity and dissolution may, with time, cause further hydrocarbon release (Meyers and Quinn, 1973).

The oil and sediment mixture can be removed from the beach by natural processes such as erosion. Sediment transport, driven by wave action, can take this contaminated mixture a considerable distance offshore. Storm-generated transport of bottom sediments on the continental shelf have been found in water depths as great as 80 m (262 ft) (Smith and Hopkins, 1972). Storms can also mix the oil with the sediment offshore. It has been observed that turbulence produced by hurricanes mixed the top 10 cm (3.9 in) of surface sediments, in depths up to 35 m (115 ft) (Hayes, 1967). In addition to transport by waves, longshore currents can also cause considerable sediment transport.

Environments: Vulnerability and Response

Coastal environments can be categorized by their coastal geomorphology and vulnerability to spilled oil. Vulnerability is primarily based on the long-term persistence of the oil, though initial biological effects are considered. Variations of oil-spill behavior will occur within each coastal environment based on ice, waves, tides, sedimentary characteristics, oil viscosity and quantity, winds, and offshore transport. By combining the information on the variable conditions within the affected coastal environment, a reasonably accurate picture of the spill behavior can be obtained, which would serve as a guideline for cleanup operations.

The major coastal environments have been classified on a scale of 1 to 10 in terms of potential vulnerability to oil-spill damage. The scale emphasizes oil persistence, with a consideration of initial biological impacts. Exposed rocky headlands and wave-cut platforms (numbers 1 and 2 on the index) are generally least affected by an oil spill. Coarse-grained, sandy or gravel beaches, which are subject to oil penetration and burial, are assigned intermediate index values of 4 to 7. Sheltered environments, such as sheltered rocky coasts and salt marshes (index values of 8 to 10) are the environments most likely to be affected by oil spills. For example, oil persistence of more than 10 years is predicted for some salt marsh areas, compared with 2 weeks for exposed rocky headlands.

Exposed, Steeply Dipping, or Cliffed Rocky Headlands--

Exposed rocky headlands are often open to high wave energy. Oncoming waves are reflected back off the rock scarps, usually generating a return flow. In the event of an oil spill, this return flow would keep most of the oil off the rocks. In addition, the great mixing action associated with the swash zone at the base of the rocks aids in the natural breakdown of the oil into smaller volumes that are more easily degraded by bacteria. Persistence of oil on rocky or cliff coasts depends on the rates of natural erosion, the levels of wave energy, and the location of the oil. For example, if the oil is splashed above the normal wave activity, it will persist longer.

Oil-spill control and cleanup is usually unnecessary on these coasts because of the low level of contamination and rapid rate of natural cleanup. However, if cleanup is desired, several techniques have been proven effective in past spills. Hydraulic dispersal, steam cleaning, sand blasting, or manual scraping can be used to remove viscous oil that adheres to rock surfaces when wave energy is low. These techniques only disperse the oil that would have to be collected and removed. Sorbent materials placed at the base of the rock would aid oil collection. If oil is deposited on unconsolidated material, these techniques are not recommended, since the cliff face would be washed away by mechanical cleaning.

Eroded Wave-Cut Platforms--

Eroded platforms consist of narrow, wave-swept beaches of eroding glacial material or platforms cut directly into crystaline or sedimentary rock that may be covered with sand or gravel. Wave action is usually high, and a natural cleansing of the beach occurs rapidly, generally within weeks. The rate of removal is a function of wave climate. The greater the wave energy, the more rapidly oil will be removed.

In most cases, oil-spill cleanup or control methods are not necessary. If cleanup is desired, several techniques are available. For medium- and high-viscosity oil, high-pressure hydraulic dispersal, steam cleaning, sand blasting, or manual scraping can be used to remove the oil from rock surfaces. For low-viscosity oil, low-pressure hydraulic dispersal is recommended. These techniques will only disperse the oil; it should be collected and removed by other methods. Sorbents would be suitable for oil collection. However, oil may flow from the rock surfaces in between the rocks and penetrate to greater depths. If this occurs, cleanup by these methods is not recommended. Where oil collects in pools or hollows, it can be burned in situ, removed manually with sorbents, or can be picked up with cans, buckets, or direct suction. This plan should be carried out before tides rise and the pooled oil is moved to adjacent areas. Otherwise, this oil could contaminate or recontaminate adjacent shoreline areas.

Flat, Fine-Sand Beaches--

Fine-grained beaches (0.0625 to 0.25 mm [.00025 to .098 in] grain size) usually have a flat profile and are hard-packed. The grains of fine sand are close together and effectively inhibit oil penetration to less than a few centimeters below the surface. Oil persistence varies over a wide range, depending upon the variables discussed in an earlier part of this section.

Several methods are available to protect sand beaches from an approaching oil slick. In areas where wave energy is low, conventional booms may be useful. In areas of low tidal range, the beach can be protected by construction of a dike or trench at the water level. This can be carried out by machinery pushing sand to the water line. In higher tidal areas, a dike would be built at or near the high-water line to prevent oil from being deposited on the back shore. Wet sand makes a more effective dike; therefore, the sediment from the intertidal zone should be used rather than dry backshore sand.

Recovery is simplified because of the flat, hard surface and limited oil penetration. A thin layer of oil on the surface can often be scraped off with a motorized scraper. Under heavier oil accumulations, with penetration depths of up to 3 cm (1.2 in) the most effective method is the use of a motorized scraper in conjunction with a motorized elevator scraper. In cases where it is not necessary to remove the oil, machinery can be used to push the oil and contaminated material into the intertidal zone. Though this may recontaminate other areas, wave action will subsequently abrade and disperse the oil, and in this way the aging of the oil is increased with the necessity of removing any oil from the beach.

Sorbents also can be spread over the beach at low tide if cleanup is planned. These mix with the oil as the oil is washed ashore and could make the subsequent cleanup easier. It has been noted that sorbents are much more effective if laid down before or immediately following the stranding of oil, since this reduces the penetration of oil into the sediments (Sartor and Foget, 1971). In-situ burning may be feasible in some situations; however, the oil may penetrate deeper into the sediments because of reduced oil viscosity. Sand-cleaning machines have been developed for the removal of oil, but these have only been used in experimental situations or for minor spills. Small amounts of oiled sand can be cleaned by a small rotary-kiln-type burner, constructed from old oil drums. Mobile equipment has been developed for removing high-viscosity oils (such as emulsified, aged, or Bunker C oils) from the surface of beaches, using screens, sieves, drums, or discs. For small spills, in areas where vehicle access is not possible, manual removal using shovels, rakes, and plastic bags is an effective technique.

Caution must be taken to wait until all the oil has drifted onto the beach, in order not to repeatedly drive over the oiled portions during the cleanup effort (further grinding the oil into the beach). Caution also should be taken to remove only minimal quantities of sand. Long-term beach erosion may become a serious problem if excessive amounts of sand are removed. If removal of sediment from the beach crest is necessary, it is advisable that the material be replaced by an equal volume of the same-sized sediment. This can be achieved using machinery to push material from backshore dunes to rebuild the natural berm.

Steeper, Medium- to Coarse-Grained Beaches--

These beaches (0.25 to 2.0 mm [0.1 to 0.8 in] grain size) are present in a variety of coastal environments, from low-energy beaches to higher-energy environments. Oncoming oil may readily sink 15 to 25 cm (5.9 to 9.8 in) into the sand and be buried by natural processes to much greater depths. Oil stranded on the beachface slope is usually abraded and dispersed rapidly by the constant movement of sediments, unless the oil layer is very thick and/or wave energy levels are low. An indicator of wave energy on beaches is the degree of beach sediment sorting, with distinct zonations of one sediment size in beaches with high-wave energy and poorly sorted sediments for low-wave energy beaches. The degree of sorting can be a useful indicator of the persistence of oil in this environment.

Oil-spill cleanup becomes very difficult where oil is buried deeply in the beach. No effective onshore protection method can be recommended; however, suggestions may be useful. Trenches and dikes, constructed at the high-water mark, can protect the backshore areas by acting as collectors of oil and thus preventing it from reaching sensitive areas such as marshes.

Recovery of oil by mechanical equipment is possible; however, it may be difficult to use on these beaches because of low traction provided by the sediments. Graders and elevating scrapers could be used if oil penetration is up to 3 cm (1.2 in). If the oil is 3 to 22 cm (1.2 to 8.7 in), use only a motorized elevating scraper. If the oil penetration is greater than 22 cm (8.7 in), use a wheeled front-end loader or bulldozer. Bulldozers are more effective on loose, coarse-grained beaches. Where steep slopes exist, backhoes could be used. Sediments can be pushed down the beqch to allow wave action to abrade and disperse the oil. Also, machinery can be used to break up oil cover, particularly if it forms an asphalt pavement crust. Sorbents spread over the beach can reduce the penetration of oil. This technique is less effective if spaces between the sediments are large, and collection of the sorbent/oil mixture is frequently a difficult operation. Manual removal may prove to be partially successful if the oil has pooled in some areas.

It is important to note that complete removal of oil-contaminated sediment could result in long-term damage to the beach. As an additional problem, heavy machinery can easily be trapped and immobilized in the loosely packed sand. Fortunately, the same high-energy beach processes that cause rapid oil burial will also remove much of the oil from the beachface within a relatively short period of time, usually weeks to months if wave action is fairly high.

Exposed, Compacted Tidal Flats--

Tidal flats are compacted, fine-grained mud or sand that are relatively exposed to wind, waves, and currents. The tidal flats are usually water-saturated, and oil does not penetrate the surface sediments because the spaces between the particles are filled with water. Most of the oncoming oil is readily moved over the surface of the tidal flat and onto the adjacent beach. Any oil remaining on the flat will be degraded rapidly by natural processes.

On wide, intertidal flats, cleanup operations could be hazardous, because of rapidly rising tides and the presence of soft patches of sand. These areas often have low bearing capacity and the machinery could get stuck. Cleanup on these wide flats is not advisable unless absolutely necessary. If necessary, cleanup activity should concentrate on manual removal of possible small oil pools left after each tidal cycle. In-situ burning may be feasible if the oil is of sufficient thickness. Machinery, such as graders and elevating scrapers, should be used only if oil coverage becomes very extensive, and they should be used with caution.

Mixed Sand and Gravel Beaches--

Beaches of this type are often located in moderate- to high-energy environments. Oil readily penetrates 10 to 20 cm (3.9 to 7.9 in) into the sediment, and burial may be rapid, possibly within a few days. Oil spilled on this type of beach may remain for long time periods.

Removal of oil can be extremely difficult without further damaging the beach. Under most circumstances, it would probably be best to let natural processes eliminate the oil on the beachface and concentrate mechanical or manual labor on the removal of oil deposited at the upper edge of the high tide swash zone. Oil will concentrate the most in this zone and, if deposited at a spring tide, will degrade at a very low rate. Methods for recovery would be similar to those described in the section on steeper, medium- to coarse-grained beaches.

Gravel Beaches--

Gravel beaches have grain sizes greater than 2 mm (0.08 in). Oil penetrates rapidly and deeply into the coarse sediments of this beach type. In addition, oil may be buried rapidly by gravel shifting under high-wave energy conditions. Oil stranded on the beachface can also be abraded and dispersed by the constant movement of sediments unless the oil layer is very thick and/or wave energy levels are low. Sediment shape and sorting are indicators of energy levels. Angular, poorly sorted materials reflect low-energy environments; well-sorted materials occur in environments with high energy levels.

A moderately- to heavily-oiled gravel beach is difficult to clean without removal of large amounts of sediment. The removal of gravel may result in possible adverse effects to the long-term stability of the beach. The oil/sediment ratio of these beaches is very low, and large volumes of material would have to be removed to recover relatively small amounts of oil.

Mechanical equipment is difficult to use on these beaches because of the low traction provided by the sediment. Front-end loaders may be partially successful in removing some of the oiled sediments. Front-end loaders with tires are preferred; however, if gravel is very loose, tracked vehicles are recommended.

As rates of sediment transport are relatively low on gravel beaches because of the large size of the sediment, rates of replacement of removed material are also low. Therefore, any material removed should be replaced by sediment of similar size. Replacement of material removed from the upper beach or storm ridge could be affected by pushing sediments from the backshore into the removal area.

Sheltered Rocky Coast--

Oil will coat the rough surfaces and tidal pools found within the numerous coves and protected embayments along the rocky coastline. The longevity of oil-spill damage is influenced by the degree of wave activity. In more exposed areas, oil will degrade fairly rapidly, but in the very protected environments, oil could remain for years.

Cleanup in this type of environment is difficult and very expensive since this environment is often inaccessible. If cleanup is desired, several techniques are available. For medium- and high-viscosity oil, high-pressure hydraulic dispersal, steam cleaning, sand blasting, or manual scraping can be used to remove the oil from rock surfaces. For low-viscosity oil, low-pressure hydraulic dispersal is recommended. These techniques will only disperse the oil that should be collected and removed by other methods. Sorbents would be suitable for oil collection. However, oil may flow from the rock surfaces in between the rocks and thus penetrate to greater depths. If this occurs, cleanup by these methods is not recommended. Where oil collects in pools or hollows, it can be burned in-situ or removed manually with sorbents and picked up with cans, buckets, or direct suction. This action should be carried out before tides rise, releasing the pooled oil to adjacent areas. Otherwise, this oil could contaminate or recontaminate adjacent shoreline areas. Only if an area is inundated with heavy oil concentrations should cleanup be considered.

Sheltered Estuarine Tidal Flats--

Protected tidal flats are common within estuaries and lagoons. Biological activity is usually high. Oil spilled in this coastal type may have long-term deleterious effects. In addition, removal of the oil contaminant is impossible without further destroying the area and its residential biological community. During an oil spill, efforts should concentrate on preventing oil from entering this environment by using booms and oil-absorbent materials. The type of cleanup procedures discussed for compacted tidal flats could apply.

Sheltered Marshes--

Salt marshes should be delineated, as part of the contingency plan, as the primary environments to receive protection upon the occurrence of a spill. Booms or absorbent material should be applied to prevent oil from entering these areas. In extreme cases, booms may be utilized to trap oil within one area to prevent it from spreading to others. Oil removal in a marsh is difficult and can result in more damage than leaving the marsh uncleaned. However, during cold seasons, biological activity will be low, and it may be advisable to pursue an active cleanup program. If the marsh is iced over, cleanup will be greatly simplified. Manual techniques of cutting oiled debris are recommended. Also, hydraulic dispersal of the oil in the marsh under low water pressure may prove useful. Often the greatest long-term damage to the marsh is inflicted by heavy machinery and the untrained people brought into the marsh to clean it. Where tidal action or seasonal plant growth is great, physical marine processes should be allowed to naturally cleanse the marsh. The Manual of Practice relating to marshlands endangered by oil spills (Maiero et al., 1978) should be consulted.

TERRESTRIAL

Permafrost

Permafrost is any earth material (soil, rock, etc.) that remains at or below 0°C for 2 or more years. Ice is not a necessary prerequisite for permafrost; however, its presence and amount in proportion to the earth material can be of great importance. Permafrost occurs, for the purposes of this publication, only in Alaska. It is commonly overlain by an active layer of varying depth and some kind of vegetative ground cover.

When an oil spill occurs in a permafrost area where snow is not present, the oil will penetrate the active layer to a depth depending on the oil viscosity, the moisture content of the active layer, the soil type, and whether or not the active layer is frozen. In summer, spilled oil may sink to the permafr ost table and then will move laterally along the top of the permafrost until the oil finds its lowest level (Wein and Bliss, 1973). The oil will not sink into the permafrost layer as long as the soil is completely saturated. (Dry frozen soils can be penetrated by oil whose temperature is above the pour point.)

Degradation of permafrost can occur through phsyical or thermal disruption of the active layer, causing thawing of both the active layer and permafrost (thermokarst). Long-term oil compaction and erosion may result from this process. If large amounts of heated oil (such as in the Alaska pipeline) were spilled in an ice-rich permafrost region, thermokarsting could result. Care in cleanup and protection methods must be taken to see that the overlying vegetative mat is disturbed as little as possible and that heavy machinery and large amounts of manpower are used only when absolutely necessary. Thermokarst problems may prove to cause much more severe damage than the oil itself.

Snow

Physical properties of snow that are important in the behavior and fate of oil include snow depth, crystaline structure, void fraction, moisture content, and temperature. When oil is spilled on snow, it will penetrate the snow and fill the void space, causing some melt water to form and some possible compaction of the snow layer.

Snow tends to absorb oil, preventing penetration into the ground layers and retarding lateral spread of the oil. Snow is also an excellent heat absorbent, as shown by Mackay et al. (1975) during an experimental spill with heated oil. In this spill, oil (at 60°C [140°F]) penetrated the snow and flowed laterally beneath it but reached ambient air temperatures (0°C [32°F]) within 5 minutes. The absorbent quality of snow will help to minimize potential thermokarst damage to the ground layers.

Snow may act as an effective physical barrier, resulting from the melting and refreezing of water and causing blockage of the pores in the snow body. The resultant ice layer prevents the oil from penetrating. In addition, if air and snow temperatures are cold enough, more viscous oils may be cooled to the point where they form their own barriers to the spread of newly flowing oil. Lighter oils may form oil/snow mulches containing 50% or more oil by volume.

Ground Cover: Soils and Vegetation

In general, oil behavior in soil is governed by oil type, soil type, amount of moisture in the soil, and ambient temperature. While few studies have been conducted on oil-sediment relationships, some generalizations can be made concerning oil behavior in soil.

When oil is spilled on the ground, it will spread on the surface as well as penetrate the surface layers of soil. Volatile components will evaporate at a rate depending on ambient temperature and wind conditions. Soil texture, soil moisture content, and oil viscosity will determine the rate and depth of penetration as well as the amount of oil retained within the material (Table 12).

TABLE 12. RETENTION CAPACITY OF VARIOUS SOILS*

Soil texture	Oil retention capacity (ℓ/m^3) or (parts per 1000 by volume)
Stone-coarse gravel	5
Gravel-coarse sand	8
Coarse-medium sand	15
Medium-find sand	25
Fine sand-silt	40

* Source: German Federal Ministry of Health, 1969.

Interacting with dry, coarse-grained sediment, low-viscosity oils will produce the fastest rate and greatest depth of penetration into the soil. As the soil moisture increases, the rate of penetration of oil will slow because of the lack of available pore spaces. In a frozen soil (permafrost or seasonally frozen), the rate of penetration is likely to be very slow and proceed only with the amount of melt that may be caused by the oil as it spreads over the ground. Finely textured soils with higher moisture content will prevent much penetration because of pore size and availability.

Vegetative ground cover may take various forms, depending on the soil type, overstory type, soil moisture regime, and latitude or altitude. In areas of thick organic mats, with either living or dead material, the organic matter acts like a sponge, soaking up the oil and preventing it from penetrating far into the soil and subsoil. In areas with little or no ground cover, oil will penetrate to a depth that will depend on moisture conditions, temperature, and soil type.

Tundra

Arctic tundra occurs north of the boreal forest in Alaska and is charactrized as a frozen plain with a vegetative cover of sedges, mosses and lichens, grasses, and low-growing shrubs. Because of the presence of permafrost, much of the flat, low-lying areas of the tundra are wet or ice-rich. The continual thawing and refreezing of the active layers makes much of the substrate unstable and, therefore, highly susceptible to disturbances, both man-made and natural. The most prevalent form of disturbance is thermokarst, where the thermal regime of the ground is disrupted. Removal of vegetation, compaction or removal of soils, and changes in moisture regimes may cause severe erosion and degradation of the area (Smith, 1974).

Protection techniques consist principally of building dikes or berms to prevent oil flow and trenching to collect oil. If spills occur in winter, dikes should be built of snow whenever possible to avoid disturbing vegetation or soils. In other seasons, or where snow is not present, dikes and berms should be made of artificial materials if they are obtainable. The use of heavy equipment should be avoided if possible; manpower at the site should be limited to that which is absolutely necessary (Allen, 1979). In winter, solidly frozen ground can provide a stable platform for response efforts. However, care should be taken to avoid disturbance to the insulating organic mat, especially where moving snow for diking purposes (Buhite, 1979).

Recovery techniques for tundra areas include direct suction of oil or flooding of the area and subsequent skimming or burning of the oil. If snow is present, recovery of oil/snow mulches should be done mechanically by hand or machine (Buhite, 1979). Theuse of heavy machinery may cause more damage than the oil itself, particularly in the summer when the active layer is thawed and can be easily disturbed. Careful evaluation of the need for such equipment should be made. In some areas, natural biodegradation processes may be the best cleanup technique available because of the potential for long-term (hundreds of years) damage from the use of heavy equipment (Everett, 1978).

SECTION 5

SURVEILLANCE

Two general applications of spill surveillance are detection and monitoring. Detection of oil alerts personnel that a spill has occurred. Monitoring is used to assist in cleanup operations; its function is to give the aerial extent, points of concentration, and drift of tracking. Knowledge of the aerial extent and drift is important for the effective placement of containment devices and the implementation of protection measures. Identification of points of concentration optimizes the positioning of recovery equipment.

Surveillance technology has advanced greatly for aquatic spills but has advanced more slowly for land spills. While several types of surveillance sensors have been developed for remote sensing of open-water spills, each surveillance sensor has at least one blind spot, or condition in which oil slicks cannot be detected (Edgerton et al., 1975). For temperate, open-water surveillance, limitations include the amount of available light, cloud cover, sea state, oil type and thickness, and observation angle. In addition to these limitations, mixing of oil with snow and ice greatly intensify problems of surveillance in cold regions.

Snow and ice may hide a slick from surveillance within hours after a spill. Oil can flow under ice, sandwich within growing ice, spread between ice floes, intermingle with fractured and deformed ice, or mix with snow. In addition, the following natural and man-related optical phenomena further complicate the oil detection and monitoring problem in cold regions:

> Prolonged darkness occurs in the more northern latitudes. The daily period of sunlight changes rapidly throughout the year in the North; for example, at Point Barrow the amount of daylight varies in less than 4 months from complete darkness to continuous daylight.
>
> Blowing snow will occur with winds of only 7 m/s (16 mph or 14 knots) in the treless plains. Blowing snow, which usually does not extend more than 10 or 15 meters into the air, may be a local condition lasting for only a few hours; however, when associated with cyclonic activity, it may last much longer. It can cover exposed oil within a few hours.
>
> Mirages, or terrestrial refraction, are caused by temperature inversions that result in above-normal refraction in the lower atmosphere. Objects beyond the horizon normally not visible may be lifted into fiew, or objects normally visible may sink below the horizon.

Optical haze, or terrestrial scintillation, blurs the landscape, increasing the problem of the identification of spills. Optical haze results from irregular refraction effects, produced by the passage of light through air with differing densities. The effect is pronounced when isolated heating of the earth causes thermal turbulence in the surface layer of the air.

Whiteout is an atmospheric optical phenomenon in which depth perception is completely lost. One appears to be engulfed in a white glow, losing all orientation. It is produced by either a diffuse, shadowless illumination or uniform white surface.

Snow blindness, or niphablepsia, results from exposure to intense, direct, and reflected sunlight. Because the sun's rays are always relatively low in the arctic region, there is an unusually high intensity of light striking the eye from below, where it is unprotected, creating this form of imparied vision or temporary blindness.

Steam fog, caused by low vapor capacity or low humidity, is an atmospheric condition present in any cold climate. Cold arctic air is easily saturated by water vapor, creating low steam fog. This clinging fog may reach an altitude of 1500 m (4900 ft) above the surface of the water.

Ice fog is a common phenomenon in the proximity of human habitation during extremely cold weather. Water vapor sublimates on hydrocarbon molecules in temperatures of approximately -37°C (-34.6°F) or colder, creating an ice fog.

Supercooled fog, or cold fog, results when droplets are suspended in the atmosphere in temperatures below 0°C (32°F).

AQUATIC

The difficulty of detecting and monitoring a spill in ice-covered waters is somewhat mitigated by the restraining effect of the ice field on oil spreading. Generally, if the ice concentration is high, one may expect to monitor a spill over a much smaller area than an equivalent spill on open water, allowing the practical application of surface-deployable techniques such as drills, augers, and divers.

Three types of spill situations are common to ice-covered waters, each having an optimum response: exposed oil in ice, oil in moving ice, and oil covered by ice. Exposed oil in ice is oil that is visible by air; for this condition, remote sensing techniques may be useful. Oil in moving ice could be detected by remote sensing (if it is visible). To trace the spill movement with respect to the ice, ice-tracking buoys could be used. Oil covered by ice most probably will be stationary, provided water currents are not fast enough to initiate oil movement (more than 3.5 cm/s [1.4 in/s] for low-viscosity oil and more than 10 cm/s [3.9 in/s] for high-viscosity oil). Surveillance techniques for detection of unexposed oil include impulse radars, augers, drills, and divers.

Exposed Oil in Ice

The most sophisticated remote surveillance package has been developed by the U.S. Coast Guard and is called the Airborne Oil Surveillance System (AOSS). This system provides remote sensing for a wide range of environmental conditions: around-the-clock visibility; clear to dense undercast; winds, calm to 30 km/hr (26 knot); waves, calm to 4 m (13 ft); and surveillance ranges in excess of 18 km (10 nmi) (Edgerton et al., 1975). This system consists of an infrared/ultraviolet line scanner, a low-light-level television camera (to be replaced by a laser-attenuated TV system), a vertically polarized X-band side-looking radar system, a 37-GHz passive microwave imager, a data annotation and display system, and a photographic camera. At present, AOSS, with the exception of the passive microwave imager, is being flown on an HC-130 aircraft. The system will be redesigned for Falcon-20 aircraft and renamed AIR EYE.

Visual sighting of an oil slick often provides the fastest, most economical way to monitor an oil spill. Visibility of an oil film is not constant, but depends upon conditions of observation, as well as upon the inherent characteristics of the oil. Visibility, of course, is limited to periods of daylight and by obstructions such as clouds, fog, or blowing snow. Optimum conditions include the absence of direct sunlight, a white overcast, a high viewing angle (approaching vertical), and low background brightness from the underlying water (Hornstein, 1972). Under optimum conditions, oil films on water as thin as 38 nm (1.5×10^{-6} in) can be detected (American Petroleum Institute, 1963). As viewing conditions deviate from the optimum, the visibility of a given oil film is reduced.

In the visible spectrum, 0.4 to 0.7 nm, the detection mechanism for oil slicks is based upon the reflective signature of oil. For oil on open water, reflectance and color effects vary with film thickness and oil type (Table 13). These relationships are very important; observers can estimate the concentrations and approximate the volume of oil on open water and between ice floes (Table14), and the cleanup strategy can be planned accordingly.

In cold regions, visual detection of oil is aided by the contrast of the surrounding snow or ice. Oil spilled in ice floes may stain the edges of the floes, making the oil visible from the air. If the ice is deteriorating, holes will appear where the oil has contacted the ice because of the accelerated melting caused by the albedo effect. Oil under ice could possibly be detected by aerial surveillance if the oil has migrated through the ice cracks and flaws at some locations. Oil and snow mixtures are easily seen from the air. However, if the surrounding snow has absorbed all the oil (the mixture being about 30% oil and 70% snow) and additional snow covers the mixture, the oil will be hidden from view. Precautions are required so as not to confuse grease ice floating on water with an oil slick.

Oil in Moving Ice

In mobile ice of high concentration (more than 50%), oil movement is closely coupled to the ice, and therefore the problem of monitoring is reduced to one of determining ice motion. In some situations regular aerial

TABLE 13. SCHEMATIC BASIS FOR THICKNESS-APPEARANCE RELATIONSHIP*

Appearance	Thickness range (nanometers)	Description
Colorless films	Up to 150	Films reflect more light than does water and look brighter. May need adjacent bare water for comparison. Apparent brightness increases with thickness. At about 75 nm and thicker, a pearly or metallic luster is usually apparent.
Onset of color	Approx. 150	First color seen is a warm tone, more bronze than yellow. As film thickens, deep violet or purple appears; these colors begin the first set of rainbow bands.
Clear rainbow colors	150 to 900	The set of bands around 300 nm are in the sequence: bronze, purple, blue, green, in order of increasing thickness. These colors are pure and intense. The set of bands around 600 nm are slightly less intense than at 300 nm, and have a modified color sequence: yellow, magenta (reddish violet), blue, green. They are quite clear.
Dull, impure colors	900 to 1500	Main characteristic is reduction in number and purity of colors. Colors at 900 nm are a rich terra cotta (brick red) and turquoise (rather bright blue-green). At 1200 nm these colors are progressively duller or less pure-looking. These sets of bands may also contain a trace of white or pale yellow.
Light and dark bands with little color	1500 to 3000	Any color present is merely a tint in the light and dark alternating bands. At 1800 nm, the contrast between light and dark bands is strong, but weakens as thickness increases. At 3000 nm, it is apparent that interference effects are weak, and they will quickly disappear as thickness increases.

* Hornstein, 1972.

TABLE 14. OIL FILM THICKNESS VERSUS SURFACE COVERAGE*

Film thickness (nanometers)	Coverage gal/acre	Coverage gal/mile^2	Coverage mg/m^2**
3.8×10^1	0.04	25	38
7.6×10^1	0.08	50	76
1.5×10^2	0.16	100	150
3.1×10^2	0.32	200	310
1.0×10^3	1.08	666	1000 (1 gm)
2.0×10^3	2.16	1332	2000 (2 gm)

* Hornstein, 1972.
** Computed values, assuming film specific gravity = 1.0.

surveillance may not be feasible or adverse weather conditions may restrict existing surveillance capabilities. In large areas of ice-covered waters, such as the Arctic Alaskan coast, it may be best to monitor the spill using ice-tracking buoys. Two types of ice-tracking buoys have been found suitable for this purpose: a macro-tracking system using a satellite-reporting transmitter, and a micro-homing system using a pulsed UHF transmitter (Blackall, 1978). The macro system allows flight to the general area of the slick, and the micro system would provide homing to the actual slick location.

The macro component has a positioning capability of absolute location on the earth's surface to an accuracy of a few kilometers (miles) and has unlimited range. On the micro scale it was recommended that a combination of an HF and UHF radio beacon and a radar reflector be used (Blackall, 1978). The advantages of these devices are low cost, high position accuracy, and compatibility with typical search aircraft. These systems have been used in the arctic for site relocation and for the recovery of oceanographic equipment.

Oil Covered by Ice

Oil under ice will collect in under-surface irregularities of the ice, provided that water currents are not strong (see Section 4). Impulse radar has the capability of mapping the under-ice surface roughness, and in this way will aid in locating oil pockets. This device has been used successfully on a sled and also flown from helicopters to map under-ice irregularities. Under some conditions, this device can actually detect oil under the ice.

The radar system produces an electromagnetic pulse generated on the ice surface, and reflections from the surface and the ice/water interface are displayed on a continuous strip-chart recorder. Travel time of the reflected pulses can be converted directly to ice thickness. System calibration is required to obtain an accurate interpretation of ice thickness. This calibration is accomplished by augering one or more holes in the ice and mechanically measuring ice thickness at loations where profile data is also recorded.

This system has been successfully used under varying conditions of first-year and multi-year sea ice and freshwater ice. Operational surveys have been performed for oil companies and geophysical contractors in the arctic to ensure the safety of on-the-ice operations and to contribute to the more economical utilization of personnel and equipment. In addition, this system has been successfully used to map the under-ice surface roughness along Prudhoe Bay (Kovacs, 1977). These measurements were then translated into potential aerial coverage by an under-ice spill.

Perhaps the most economical, and certainly the simplest, technique for checking the underside of the ice is to drill a hole through the ice. However, the technique is very labor-intensive and is an inefficient trial-and-error procedure. A search pattern should be established, based on the maximum likelihood of detecting oil from a discharge, given the spill volume, currents, and an indication of the under-ice profile before drilling is attempted. Ice surface features may provide a useful indicator of oil concentrations. These indicators include hard-packed snow drifts, which insulate the ice and limit ice growth, forming an under-ice undulation.

Augers and drills suitable for this purpose include hand-operated Russian and Sipre corers, hand-held powered augers, and truck-mounted drills. Sipre and Russian corers allow a core to be taken out in one solid piece. They have been used extensively for ice research. The Sipre corer cuts a 7.6-cm (3-in) diameter core, and the Russian corer produces a 12.7-cm (5-in) diameter ice core. Because these devices cut a clean hole without any additional contamination (for example, from lube oil), they are ideally suited to collect oil samples for both research and legal purposes (Figure 19).

The use of a portable powered auger provides a suitable means of surveying the ice. Starting problems may be encountered in very cold weather. It is estimated that a two-man crew with a portable power head could auger over 10 holes per hour through ice up to 2 m (6.6 ft) thick (Logan et al., 1975).

Truck-mounted drills may be suitable for use if the ice is strong enough and if the spill volume is large. Commercial drilling units that could be used in such an operation include the Nodnoell drill, which weighs 11,340 kg (25,000 lb) and can drill a 10-cm (3.9-in) hole through 1.8 m (5.9 ft) of ice in approximately 5 min. Another commercially available drill is the Ingersoll-Rand T-5 Drillmaster, which was used for drilling piling holes in the construction of the trans-Alaskan pipeline. The drilling unit weighs 38,500 kg (85,000 lb), and it is capable of drilling a 60-cm (23.6-in) diameter hole through 1.8 m (5.9 ft) of ice in 4 min. Problems may occur when using truck-mounted drills. For example, as soon as the drill passes through the ice, it may spray the pocketed oil over the ice surface, making recovery more difficult (Schultz et al., 1978).

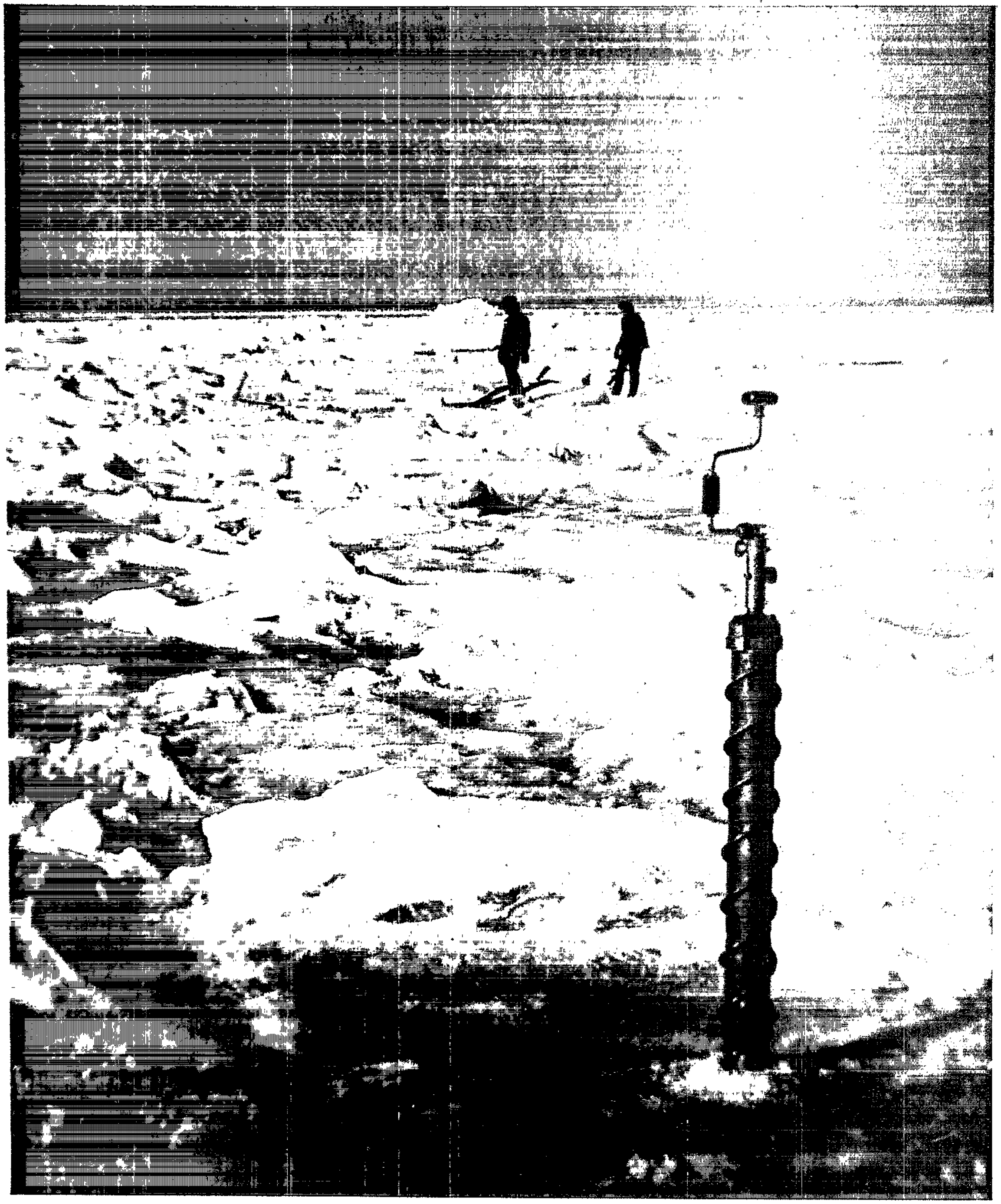


Figure 19. Sipre corer.

Divers have proven to be useful in observing oil-spill behavior underneath ice in two field experiments (NORCOR, 1975; Quam, 1978). Sufficient light is required to see the contrast of oil against the ice. Oil concentrations could be mapped if radio communications are provided with the surface, using some means of identifying diver locations. This method is not recommended in high-water currents.

COASTAL/TERRESTRIAL

In land spills, the limits of oil seepage must be found so that recovery wells can be placed at optimum points. When groundwater or permafrost is near the surface, inspection pits are dug (Betts, 1973). These pits provide the best means of assessing the oil spread and double as recovery points. Holes dug by augers can also be used for inspection.

Deep groundwater or permafrost require the use of drilling devices. These devices can be hand- or machine-operated, and can be rotary or percussion types. Large-scale investigations involving very deep groundwater or permafrost will usually require the services of a specialized drilling contractor. Caution is necessary in all drilling operations to avoid drilling deeper than necessary, since disruption of impermeable soil layers may allow the oil to seep deeper. The position of deep groundwater levels can be measured with the aid of a paste that changes color when immersed in water. The paste is applied to a rod inserted down a bore hole on a measured lead. Drills and augers must be cleaned before each insertion to prevent contamination of the samples. Similarly, when using powered drills, oil or grease from the driving parts of the drill must be kept away from the drill head.

Several techniques are available for testing soil samples for the presence of oil. The most common method of testing soil samples is by smell. This should preferably be done by several people immediately after the sample is obtained. However, in the vicinity of a recent oil spill, background odor can mask any odor from the sample. A far more reliable indication of the presence of oil in the soil samples is the presence of visible oil, particularly in the case of a volatile product (Betts, 1973). Chemical analysis of soil samples can also be employed, but this is rarely appropriate because of time and cost.

In heavy snow-covered areas, hot oil may melt a cavern under the snow, and the oil can flow a considerable distance under snow cover without being detected from above. In addition, after an adequate volume of snow falls to produce saturation of the snow/oil mixture, any additional falling or blowing snow accumulates on the surface of the mixture with no further absorption of oil by the snow. During heavy snowfalls, this covering may occur within hours of the spill, further aggravating the spill location problem.

Probing is one of the easiest and most economical ways to map the areal coverage. Probing can be accomplished by using heavy construction equipment in heavy snow covers (where ground conditions permit), or by using men with shovels for small spills.

Gas analyzers or sniffers could be useful in detecting oil under ice, in soil or in snow, provided some gases are released. Gas analyzers operate by detecting the decrease in energy in the incoming radiation resulting from the presence of an absorbing target gas. Standard instruments can detect as little as 250 ppm, by volume, of hydrocarbons in air; highly sensitive instruments can detect less than 25 ppm (American Petroleum Institute, 1972). NORCOR Engineering and Research Limited successfully employed a gas analyzer on the ice surface during their 1974/75 oil field studies for the Beaufort Sea (NORCOR, 1975). In a gasoline spill at Nenana, Alaska, the initial extent of contamination and the acceptability of the final cleanup were determined using a gas analyzer. The spill area, which had a snow cover, was mapped by digging holes at numerous locations and inserting the sniffer probe near the bottom of each hole (Allen, 1979).

SECTION 6

CONTAINMENT

Once a spill has occurred, the most important initial action is to attempt to contain the oil. A wide variety of containment barriers and methods have been developed for spill response. Containment barriers are designed to be capable of:

1. Retaining oil slicks and preventing further movement,

2. Concentrating oil slicks to aid recovery, and

3. Serving as a diversionary or protection barrier to keep the oil out of a specific area.

Nearly all commercially-available barriers have been developed for use on water, where the oil is highly mobile, with only a few basic methods available for land.

In aquatic spills, boom performance is affected by wind, waves, currents, and -- in cold regions -- low temperatures and ice. Waves can cause booms to fail by splashing oil over the freeboard if the wave steepness (wave height divided by wave length) is greater than 0.08 and the waves are higher than the freeboard (Logan et al., 1975). Wind and waves acting together make a slick hard to contain, but water currents, or the relative velocity between the boom and the water, generally provide the force that causes booms to physically fail.

Containment barriers, positioned perpendicular to the current, are effective with only slight oil loss until the current exceeds 51 cm/1 (1 knot), at which time oil droplets form at the leading edge of the slick and are swept under the barrier. As the current increases to roughly 77 cm/1 (1.5 knots), the oil loss increases by a factor of 10. The upper limit of any useful containment for the majority, if not all, booms is 154 cm/s (3 knots). Even at a water velocity of 102 cm/sec (2 knots), most booms become ineffective (Isakson et al., 1975).

In cold regions, the usefulness of many booms is further limited by the additional environmental conditions, such as low temperatures, stable ice covers, broken ice fields, moving ice floes, and snow. Moving broken ice floes create the worst containment situation, with few practical solutions. These problems are partially balanced by the natural reduction of oil spreading as a result of cold temperatures, the effectiveness of ice as an oil barrier, and the ability of snow to absorb oil. However, low temperatures can result in:

1. A reduction of barrier buoyancy because of icing,

2. A decreased ability to conform to waves caused by material stiffening,

3. Deployment and retrieval problems, and

4. Cracking of the boom material.

Containment barriers come in a wide variety of sizes and shapes, and their operation is based on a wide variety of principles. The following subsections discuss the most practical available containment techniques for cold-region use and also discuss boom deployment. For aquatic spills, these include open-water booms, oil-ice booms, and ice slots.

In coastal and terrestrial situations, the appropriate procedures for containment include the construction of trenches, dams, dikes, berms, and the use of water spraying.

AQUATIC CONTAINMENT

Open-Water Booms

In cold regions, the usefulness of most commercially-available open-water booms is severely restricted by ice and low temperatures. However, some booms can be applied in limited broken ice conditions. Their usefulness can be determined by examining the boom construction.

Variations in boom construction (see Fig. 20) are affected by the design of its basic components, as shown in the following (Deslauriers and Schultz, 1976):

The skirt or barrier material may be:

- Rigid
- Semi-rigid
- Flexible

The flotation member may consist of:

- Air-inflated tubes or pockets
- Internal or external rigid or flexible foam
- Crimped plastic tubes entrapping air
- Spherical hollow plastic beads

Placement of the flotation may be:

- Integral with the curtain or wrapped within the curtain
- Mounted external to the curtain

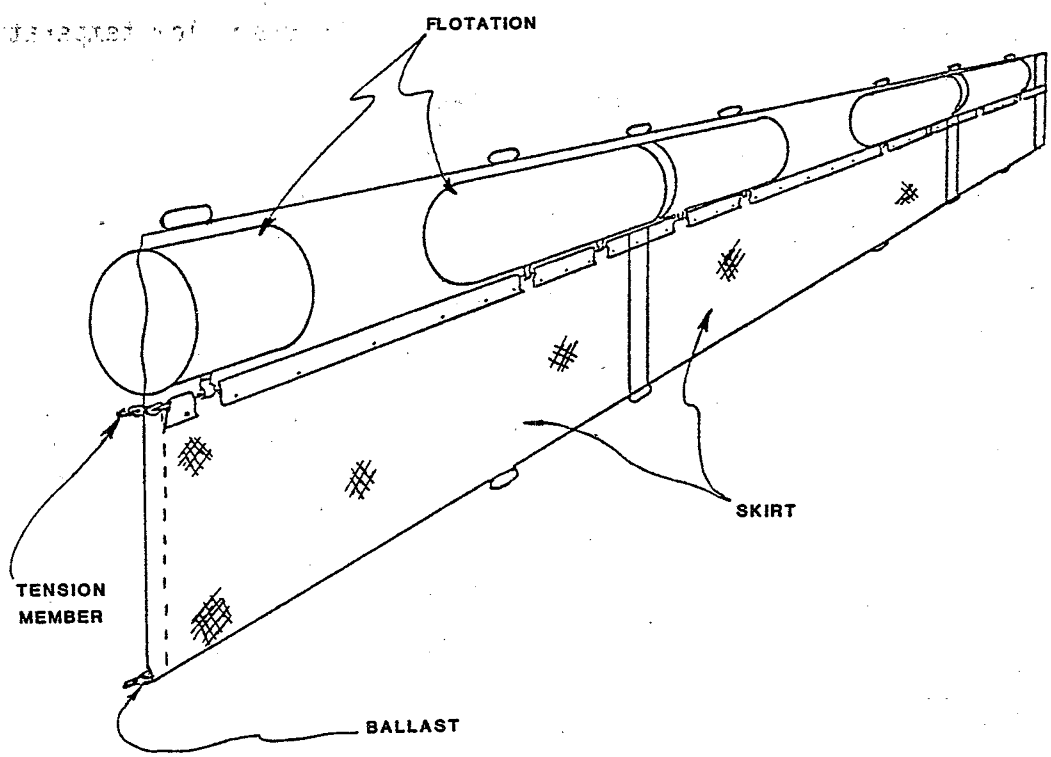


Figure 20. Oil containment boom components (Deslauriers and Schultz, 1976).

- o Continuous or intermittent

Placement of the ballast may be:

- o Continuous cables or chains attached to the bottom of the boom
- o Individual lead or steel weights attached to the bottom of the boom

The tension member can be:

- o The curtain material itself
- o Steel cable, synthetic rope, or chain placed internally or externally

Differences in structural design and the ruggedness and temperature resistance of the boom material are important factors to consider when assessing the applicability of various containment booms for use in cold regions. U.S. Coast Guard field tests on 10 oil-containment barriers in Kachemak Bay, near Homer, Alaska (Getman, 1975) found certain constructional features to be best suited for use in cold regions. These features include smooth sides, non-inflatable buoyancy members (in view of the possibility of ice puncture), tension members integral with the boom, strength suitable to withstand some ice loads, connectors easy to manipulate with gloves, additional reserve buoyancy (to counteract the potential loss of boom flotation because of icing), and boom material that maintains its flexibility and strength at cold temperatures.

It should be stressed that booms are not meant for use where large ice floes are present, with concentrations greater than 10% to 20%, or where ice fields are moving. It may be found that if there are no suitable means to allow accumulated ice to pass, eventually either the boom will fail or the ice will restrict the oil from getting to the recovery devices. Light-duty containment booms have potential for use in skim ice conditions. Medium-duty booms are suitable for light brash ice conditions. Heavy-duty booms are suitable for use in the presence of small broken ice pieces. If ice accumulation becomes heavy, the booms should be capable of allowing the ice -- and any oil collected with the ice -- to pass beneath them.

Deployment of Booms

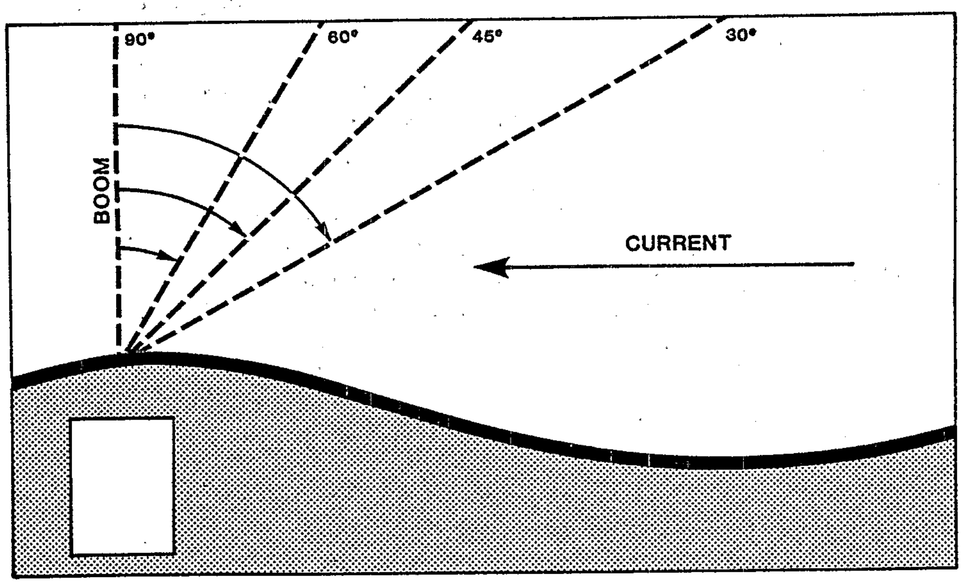
Speed in deploying a boom is essential. Selection of appropriate deployment techniques depends upon the type of water body (for example, rivers, bays, or open water), velocity of water currents, land form and water body configurations, depth of water, presence of breaking waves, amount of oil to be contained, and the type of ice conditions present. Deployment techniques include exclusion booming, diversion booming, and containment. A brief discussion of each of these techniques follows. For more detailed information, refer to the Manual of Practice for Protection and Cleanup of Shorelines (Woodward-Clyde Consultants, 1979).

Exclusion Booming--

Exclusion booming is used across small bays, harbor entrances, inlets, and river or creek mouths, where currents are less than 1 knot and breaking waves are less than 25 cm in height. The current velocity can be measured by timing a floating object that is mainly submerged over a distance of 30 m (98.4 ft). A time of 60 s or longer over this distance indicates a water current of (at most) 0.5 m/s (1 knot). The boom may be placed across or around sensitive areas and anchored in place.

Diversion Booming--

Diversion booming should be used where waves are less than 25 cm (10 in) and the water current is greater than 0.5 m/s (1 knot) or when the area to be protected is so large that the available boom would not be sufficient to contain oil or protect the shoreline. Diversion booming is useful for diverting oil away from sensitive areas to other shoreline locations that are less sensitive and/or more easily cleaned up. The booms may be deployed as a single section, as multiple booms staggered across a channel, or in conjunction with berms or river bars. Diversion booms should be deployed at an angle from the shoreline closest to the approaching oil slick to divert oil toward shore, where pickup of pooled oil is easier. The faster the water flow, the greater the boom angle should be to prevent oil from going under the boom (Figure 21 and Table 15). The more acute the angle, the greater the length of boom required, so that there is a practical limit to the use of the angling technique. Booms have been successfully employed using this technique in currents up to 1.2 m/s (2-1/3 knots). Successful use requires a boom length of three



CURRENT, Knots	1.5	1.6	1.7	1.8	2.0	2.3	2.6	3.1	3.8
BOOM ANGLE, ° for V_{eff} = 1.3 knots	70	65	60	55	50	45	40	35	30

Figure 21. Placement of boom to offset different current speeds in flowing water (Betts, 1973).

times the river width. When deploying the booms in swift currents, the boom forms a catenary (or J shape), and there may be loss of oil at the apex. To make the boom more horizontally rigid, several anchored guys are required, or deflectors or rudders along the boom can be used to reduce the catenary (Brodsky et al., 1977).

Containment Booming--

Containment booming is used on open water to surround an approaching oil slick, as a means of protecting shoreline areas where surf is present or where the oil slick does not cover a large area. This type of booming is used also on inalnd waters where currents are less than 0.5 m/s (1 knot). The boom should be deployed downwind or in the direction of the surface current, around the leading edge of the floating slick, and then back into the wind or current. When the boom is deployed, it forms a U shape in front of the oncoming slick. The ends of the boom are anchored by drogues or work boats. Containment efforts should concentrate in areas where the slick is thickest, which is where it takes on a dull or dark appearance. These thick pools may contain nearly 90% of the spilled oil, in an area about 1/8 of the total slick area (Jeffrey, 1973; Mackay, 1977).

Anchoring requirements for exclusion and diversion booms can be a problem, particularly if ice pile-up on the boom creates abnormal boom tension. If moving ice is present, it is important that the boom have the ability to

TABLE 15. RELATIONSHIP OF CURRENT AND VELOCITY TO BOOM ANGLE*
(1 knot = 51 cm/s, 1 ft/min = 0.305 m/min

Current (knots)	Velocity (ft/min)	Boom angle (for effective speed of 1.3 knots)
1.5	150	70°
1.6	159	65°
1.7	170	60°
1.8	184	55°
2.0	202	50°
2.3	227	45°
2.6	260	40°
3.1	307	35°
3.8	380	30°

* Source: Betts, 1973.

ride over the ice when tension is high; otherwise, the boom or mooring will fail. When a boom is anchored to a shoreline, it can be attached to large boulders or trees by a cable sling and shackles. Frozen ground adds to the problem of establishing suitable anchor points. When an anchor is used, a line approximately twice as long as the water depth is attached to the anchor. The other end is fixed to a buoy float, which is then attached to the boom with a short piece of line. The buoy float prevents the boom from being dragged underwater by the pull of the anchor.

Oil/Ice Boom

The combination of an ice retention boom and oil containment boom can be applied in moving ice of limited size and concentration. When oil is spilled in rivers with drifting ice floes, conventional containment booms and recovery apparatus have great difficulty in performing their functions. The ice floes will rip conventional booms apart if significant ice accumulates behind the boom and will jam the intakes of recovery machinery. To effectively contain oil in moving ice, an ice-free area must be created. To do this, a barrier can be set up that, while permitting the oil slick to pass through, will bar ice floes from entering the area. This type of boom has been developed by Dr. G. Tsang (Tsang, 1975; Tsang and Vanderkooy, 1978).

The double-boom system consists of a perforated ice-retention boom designed to pass the oil and divert the ice, with an inner open-water boom for oil containment. To reduce mooring requirements, the Tsang boom is held out by a number of short fins or rudders (Figure 22). The angle between the boom and the fins is adjustable. The upstream end of the boom is tied to the shore. As the fins are gradually opened, the force of the current on the fins brings the boom into the flow. Very large floes, or high ice concentrations, push the boom toward shore, thus preventing boom and mooring damage. Openings are provided in the boom for the oil slick to pass through. Tests have shown (Tsang and Vanderkooy, 1978) that approximately 95% of simulated oil passed through the opening.

This approach to containment appears to be the most realistic containment concept presently available for moving ice conditions. The prototype performed well at Amherstburg, Ontario. Further tests are presently planned in Alberta and on the St. Clair River. This type of boom may be useful to have in certain EPA districts. More information on design specifications can be obtained from Dr. Tsang at the Canada Centre for Inland Waters, Burlington, Ontario.

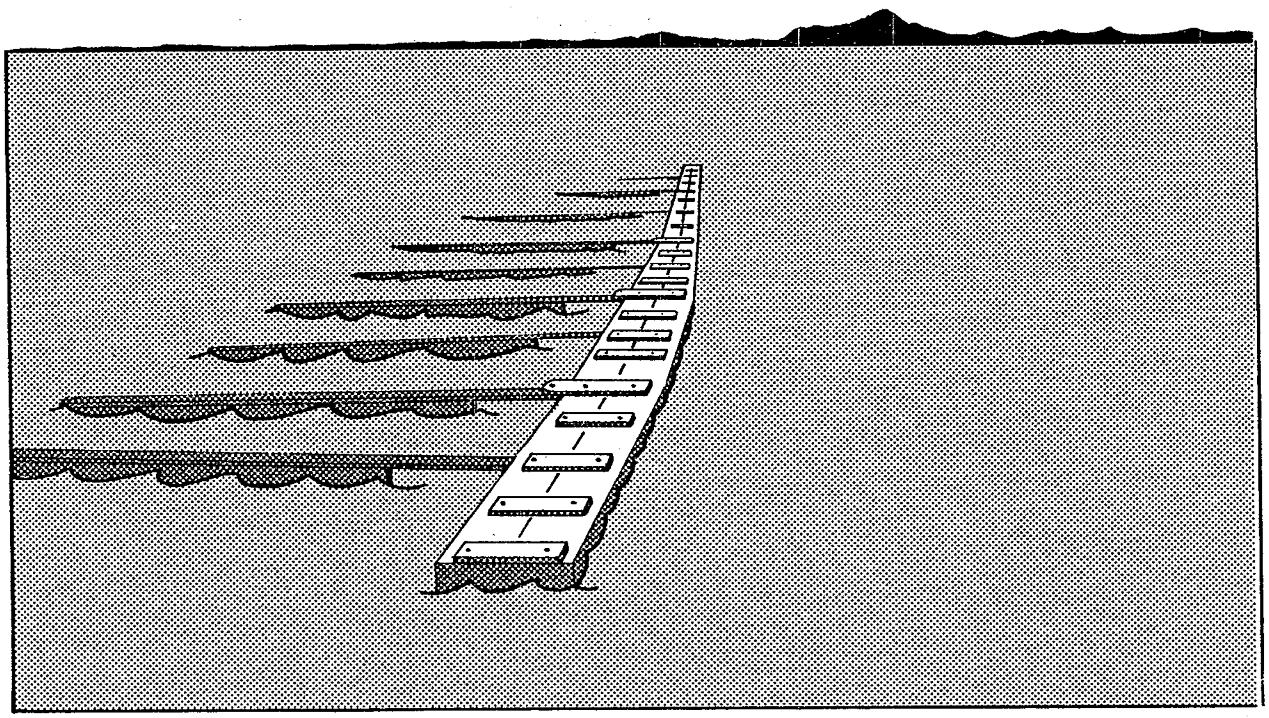


Figure 22. The Tsang boom (Tsang and Vanderkooy, 1978).

Ice Slotting

Oil moving under solid ice can be intercepted and contained by slotting the ice cover. Laboratory and field tests (Quam, 1978) have verified this technique as an important spill response. From laboratory experiments, it had been found that ice slots at a 30° angle to the current, with a width 1 to 1.5 times the thickness of the ice, were best for oil containment. The ice blocks were cut by a Ditch Witch and chain saw and then removed with a crane (Figure 23) (Quam, 1978). Oil released under the ice upriver generally maintained contact with the underside of the ice and travelled at a maximum 25% to 30% of the average current velocity. The oil surfaced rapidly in the recovery slot and was easily removed. Water quality monitoring indicated that very limited quantities of spilled oil passed under the slot. It was established that a slot 1.2 x 1.2 m (3.9 x 3.9 ft) would hold about a 13-cm (5.1-in) layer of oil on the water surface in an ice thickness of 71 cm (28 in) and an average current velocity of 0.5 m/s (1 knot).

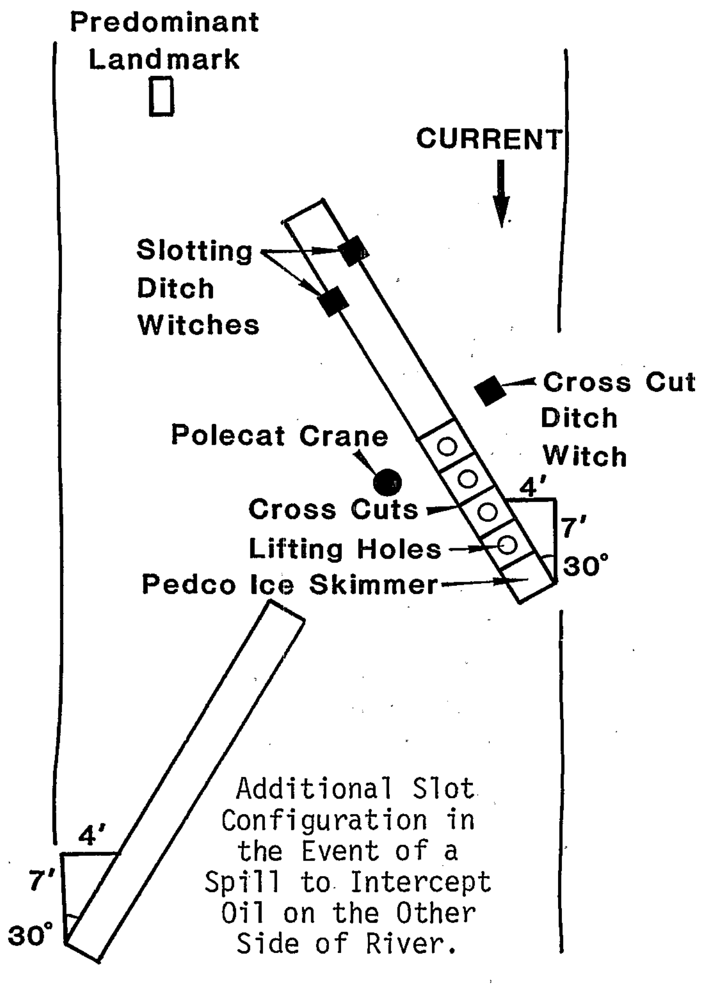


Figure 23. Ice slot installation (Quam, 1978).

Implementing this technique first requires planning the location of the ice slots, which should be downcurrent of the moving slick. The next step is to make slots in the ice and to remove the ice from the slots. Slotting techniques include using a trencher chain saw or circular saw. The ice blocks are lifted out with a crane or pushed under the ice. The ice blocks can be lifted by using a T-bar inserted through the drill holes of ice blocks and hoisted out by a crane. Smaller equipment, or men working with hand tools, could push the ice blocks under the downcurrent edge of the stable ice. Once the blocks are removed, ice chips and slush ice should also be removed from the slot.

The problem in using the ice-slotting technique is in locating the best place to recover the oil. Accurate prediction of slick location is beyond the state of the art. Heavy equipment may be required to slot thick ice. In cold temperatures, the slots may refreeze fairly rapidly. Oil and water may travel up over the ice, spreading onto the top of the ice. In thin ice, a trench will alter the structural properties of the ice sheet. In spite of these problems, ice slotting shows potential as an aid in spill response in solid ice.

COASTAL AND TERRESTRIAL CONTAINMENT

Trenches and Dikes

Trenches and dikes are useful to collect oil from terrestrial spills and to protect the upper beach and backshore areas of sandy, low-energy coasts. The need for terrestrial containment is primarily in the warmer months. During the winter, ice and snow will serve as natural containers and sorbents of oil and will prevent percolation into the soil. However, rapid absorption into the soil during spring and summer months is quite possible, so methods should be employed to contain oil, especially if the spill occurs before the spring thaw. The meltwater would inevitably spread the oil over large areas if precautions are not taken to contain it.

If oil has percolated into the soil, trenches are particularly useful in containing and intercepting the spill. On sloping terrain, the oil follows the topography and takes the route of steepest descent, following water drainage channels. Trenches should be dug in the path of the oil flow. In areas where permafrost exists, precautions should be taken. Ideally, the containment method should involve minimum disruption of the area and should avoid removing the active soil layer and exposing permafrost. Whenever possible, trenching operations should not depend on heavy equipment, which is likely to compact and destroy the active layer. The trenches should be dug down to an impermeable layer, such as permafrost, water, or clay. Tests in permafrost (Mackay et al., 1974) showed this to be an effective means of containing and preventing subsurface spreading with only a relatively small amount of oil seeping beyond the trench. Therefore, the oil can be controlled by offering a zone of low resistance to the oil flow.

Upper sandy beaches or backshore areas may be protected by construction of dikes or trenches parallel to the water line near the highwater level. In construction of a dike, wet sand pushed up from the intertidal zone makes a more effective barrier to oil, as it is possible to construct a higher dike than if dry backshore sand is used (Owens, 1977). The dikes should be approximately 2 m (6 ft) wide and 1 m (3 ft) high, but these are dependent on the maximum height of the incoming tide (Woodward-Clyde, 1979). The use of tracked vehicles for construction is recommended because of the need for traction in sand. Observations of tidal action on constructed dikes indicate that they could successfully protect backshore areas for at least one tidal cycle (and possibly two), assuming no large storm waves or winds occur (Woodward-Clyde, 1979).

Trenches can be dug to act as collectors for oil (Figure 24). When water and oil run up into the trench, water is drained out through the beach sediments. Oil in the trenches can then be removed with cans, buckets, pumps, or vacuum skimmers. These methods are less effective on coarse sediment beaches, since the oil can penetrate into the substrate. Nevertheless, a dike at the highwater mark would collect oil within the pebble-cobble sediments and protect sensitive backshore environments such as marshes and lagoons.

Water Bypass Dams

Water bypass dams are used to contain oil in drainage courses that have little or no water flow (Woodward-Clyde, 1979). The dam should be constructed where there are high banks buttressed to support oil and water pressure. Construction materials can include earth, snow, sandbags, or other materials that block flow.

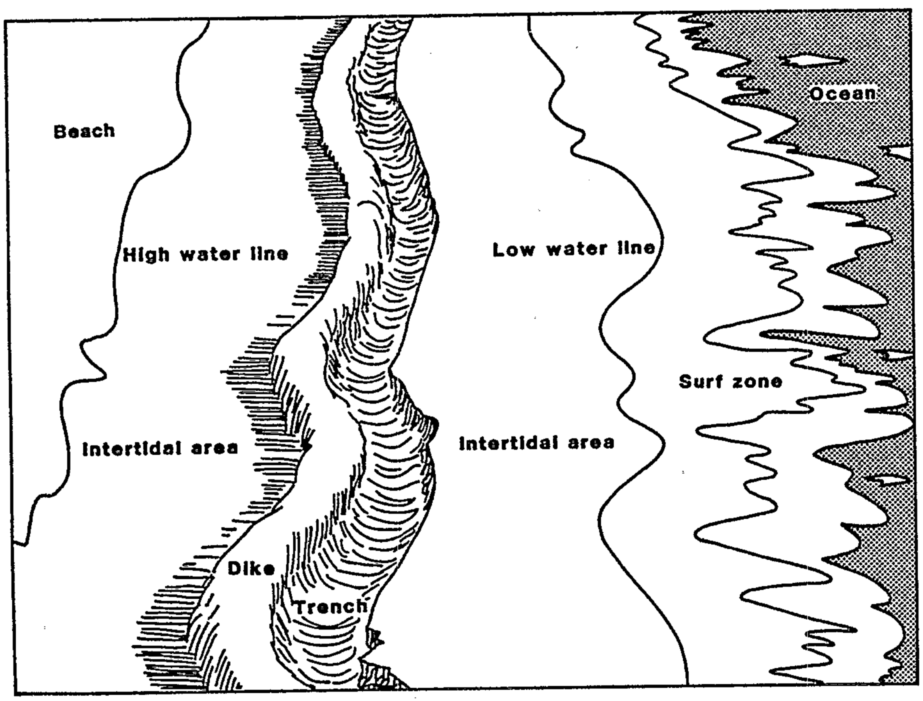


Figure 24. Dike and trench (Woodward-Clyde, 1979).

Water trapped behind the dam can be pumped by placing a hose near the bottom. Trapped water can also be moved across the dam with siphons. For higher water velocities, pipe or tube can be used (Figures 25 and 26). The diameter of the pipe used will depend on the flow rate of the stream and the depth of the water behind the dam. For example, 60- to 76-cm (23.6- to 29.9-in) diameter pipe will have sufficient capacity for a flow rate of up to 0.85 m^3/s (30 ft^3/s).

Problems such as upstream flooding may result from ice buildup. In this case it may be necessary to remove some of the ice if water flow is restricted.

Snow Berms

Snow berms may serve as an effective barrier to oil spilled on the surface. Berms can be made easily with heavy construction equipment or snow blowers, or they can be built manually. The barrier also can be established using empty oil barrels as a wind break, allowing snow to drift against them. During field tests (NORCOR, 1975), the oil did not penetrate more than 15 to 20 cm (5.9 to 7.9 in) into a snow berm. If the barrier is breached, holes can be patched quickly with snow. The snow can be sprayed with water during freezing temperatures to form a more solid barrier.

Water Spraying

Oil penetration into beach sediment and soil can be minimized by forming a protective ice covering. This covering can be formed by spraying water lightly on the beach in freezing temperatures. The likelihood of this being accomplished before a spill strikes an area is slight; however, this technique would be very practical if the opportunity arises.

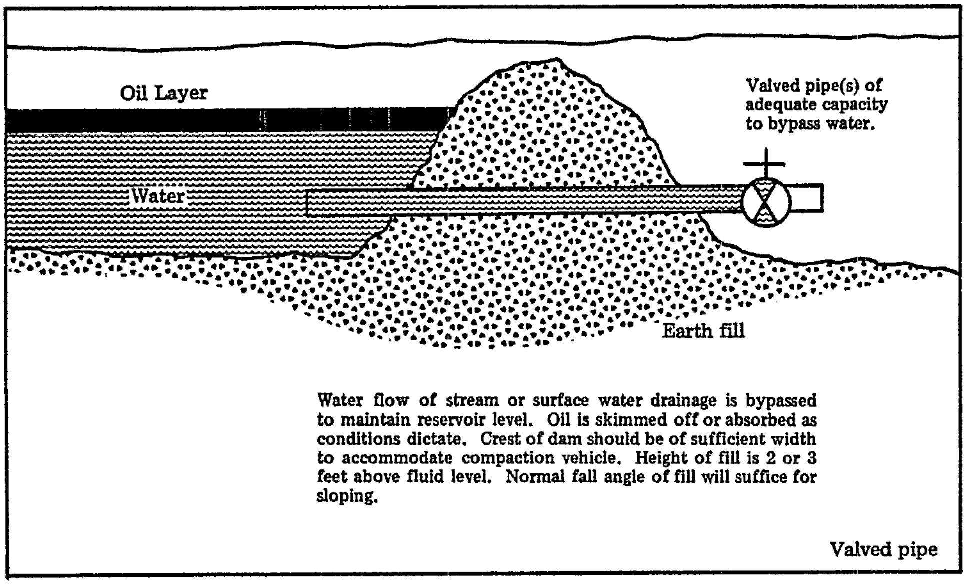


Figure 25. Water bypass dam (valved pipe) (Woodward-Clyde, 1979).

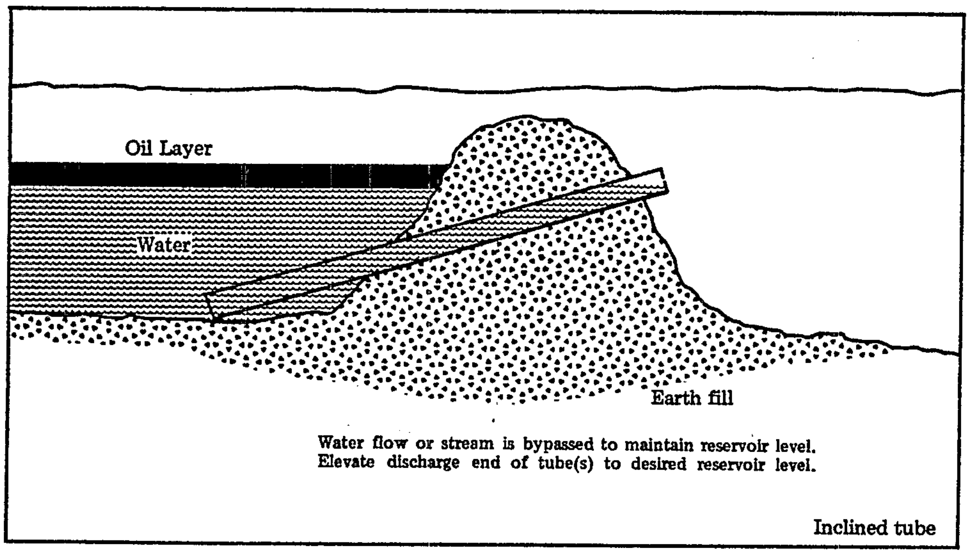


Figure 26. Water bypass dam (inclined tube) (Woodward-Clyde, 1979).

SECTION 7

RECOVERY

AQUATIC

Mechanical Recovery Devices

A great variety of mechanical oil-spill recovery devices has been developed for use on open water. These devices lose effectiveness if wave height exceeds 0.46 to 0.61 m (1.5 to 2 ft) or if current exceeds 31 to 46 cm/s (0.6 to 0.9 knot). In cold regions, moreover, freezing temperatures can make a device inoperable because of icing or failure of seals and bearings due to increased viscosity of the spilled oil. Ice conditions can range from light slush to large ice floes of varying concentration, interfering with oil recovery devices.

Most mechanical systems can be modified for operation in remote cold regions through changes in handling techniques, materials, the addition of insulation, or the addition of localized heating. Rubbers and plastics must be carefully selected to provide good service at low temperatures. Synthesized hydrocarbons specifically formulated for cold-region applications should be used in all lubricant and hydraulic systems. Consideration should be given to in-line air dryers, heaters, alcohol injectors, and in-line lubricators for pneumatic systems. Electrical insulation must be carefully selected for flexibility at low temperatures. The handling aspects of all equipment must allow for the fact that very heavy, bulky clothing required in cold regions severely restricts the manual dexterity of personnel. As a result, all handling and fastening devices must be simple mechanisms, and all access openings must be extra large. In addition, because of possible icing, safety shields should be installed around all moving parts. Finally, the equipment should be packaged in small containers because of the possible unavailability of conveyance devices in remote cold-region areas such as Alaska.

Mechanical oil recovery devices, commonly called skimmers, are classified into five groups: weir, belt, disc, drum, and vortex devices. In addition to skimmers, mechanical recovery can also include direct suction of oil from pooled areas and the direct removal of oil-contaminated ice. A description of various mechanical recovery methods will be given with reference to previous testing and experiences in cold regions. Drum and vortex skimmers will not be discussed since their use in ice-infested waters has not been successful.

Weir Skimmers--

Oil floating on the surface of the water is separated by passing over the weir that holds back the water. Weir-type skimmers come in a great variety of shapes and sizes, ranging from the very small hand-held variety to the relatively large vessels or barges.

In cold regions weir skimmers are clogged by broken ice pieces in the recovery intake, and suffer icing resulting from water spray that could change the ballast of the skimmer. In broken ice, a weir needs a debris grid or screen to avoid rapid clogging by broken ice pieces. With a debris grid or screen there is still the problem of broken ice greatly restricting the flow of oil to the skimming device.

A weir-type skimmer may be effective in cracks, leads, and polynoyas that occur in regions of solid ice cover. A related application might consist of employing a weir device in conjunction with ice slotting. The slotted ice would essentially provide an open-water region in the solid ice cover that would act as a reservoir for the spilled oil. The weir-type oil spill recovery device could be used in the slot to remove oil from the water surface.

Heating elements on the skimmer may be effective in preventing ice crystals from forming and adhering to the leading edge of the weir. A heating element would be an important addition to these types of devices when used in below-freezing temperatures in ice-free areas. It is also possible to use the weir device in broken ice fields in conjunction with an ice-processing device that would clear ice for the weir skimmer.

Belt Skimmers--

Belt skimmers use a flexible belt that is drawn through the oil. The oil adheres to the belt and is then scraped off or squeezed out of the belt into a collection sump. Several belt materials can be used, including steel, nonporous fabrics, porous fabrics, and stranded fabrics. The belt configuration also varies from belts resembling conveyor belts to circular tubes and stranded rope. The devices that use nonporous belts typically depend upon the coating characteristics of the oil on the belt surface and on the subsequent removal of the oil from the belt with a wiper. The belts that have a porous or stranded nature collect oil on the surface and within the pores or strands. Generally, a wringing mechanism of some type is used to remove the oil from the belt.

Belt skimmers cover a wide range of sizes from small hand-held units to larger units installed on offshore vessels. They also vary widely in the placement and direction of the belt movement. The belt can be arranged in a vertical position or at an angle to the water surface, and it acts in a way similar to a conveyor. Some units depress the oil along a moving belt downward below the water surface. Systems are also available in which the moving belt floats on the surface of the water being skimmed.

Three belt units show potential for use in cold regions, though all may have problems collecting highly viscous oils. These belt units are the Oil Mop, the Marco Filter Belt, and the Shell Zero Relative Velocity (ZRV) skimmer.

The Oil Mop spill recovery system consists of a plastic rope mop that absorbs oil and rejects water, pulleys to expose the mop to floating oil, and wringers to clean the mop of the absorbed oil. The rope forms a continuous loop threaded through the wringers that provide the motive force for moving the rope through the oil.

The Marco filter belt skimmer collects oil by absorbing it in a synthetic foam material with a stranded, open-cell construction that permits water to float through the open cells while oil is trapped within it. After the oil becomes attracted to the belt, it is transported to a squeezer and scraper, where it is removed. A characteristic of the Marco unit, which could prove advantageous when recovering oil in broken ice, is the tendency for this unit to recover small, oil-coated ice pieces. While the recovery of slush ice and small ice pieces may be desirable in some field applications, it adds to the problem of transfer, storage, and disposal.

The Shell ZRV system uses an endless, sorbent belt driven at a speed matching that of the water moving past the skimmer. The velocity difference between the device and the water layer is reduced to near zero, minimizing the entrainment of oil droplets as a result of little turbulence. The system uses a continuous belt contacting the water for 12 m (40 ft) to allow a long contact time for absorption of oil. Belt tension is kept low so that the belt conforms to the shape of the waves and may move over ice fragments in broken ice fields. The belt has a polypropelene surface for the absorption of low-viscosity oils. Oil is squeezed from the sorbent belt by passing it through a wringer consisting of a perforated drum and conveyor belt.

Disc Skimmers--

The disc type of skimmer typically consists of a series of vertical discs that are rotated into the slick. The oil adheres to the disc as it rotates through the slick and is wiped off by a series of wipers into a sump.

The only disc device showing potential for use in a broken ice field is the Lockheed Clean Sweep, which consists of a series of relatively closely-spaced discs. Oil adheres to the rotating discs, and it is wiped off by a series of stationary wipers into a central collecting trough. A conveyor screw located in the trough moves the oil into a collection sump.

One of the major advantages of the unit is that the rotating drum submerges broken ice pieces and the oil between the ice pieces is made accessible for recovery. If some oil adheres to the surface of the ice pieces, the oil tends to float free and can be recovered by the device. Though this device does show promise for use in broken ice, several problems exist with operation in cold regions. High-viscosity oil does not flow through the veins to the disc but merely coats the outside surface of the drum with a heavy oil layer. Also, the equipment weighs over 7 tons.

A second disc-type device that has been tested for arctic use is the Morris skimmer (Morris, 1979). This device has rotating discs that pick up the oil. The oil is scraped off and transferred to a central collection area. However, this device does not have the in-processing ability. This device proved to have adequate performance in recovering oil with viscosities of 2000 centistokes at 0°C. The device also performed well at air temperatures of -14°C and water temperatures of -3°C. Though these devices show promise for use in cold temperatures, they will encounter problems when used in a broken ice field.

Direct Suction--

Direct suction by pumps (see Section 9) and other transfer systems, such as vacuum trucks, is one of the most successful cleanup techniques used in cold regions. The reasons for success are that oil slicks tend to be thick and oil pools are often present. The thick slicks are due to increased oil viscosity, caused by low temperatures. In addition, the natural containment of snow and ice has proven to be a great aid to direct suction in many spill incidents.

The major problems in using direct suction for oil recovery is that water taken in with the oil must be separated later. In addition, small ice pieces may be taken into the hose, or water taken into the hose could freeze, thus restricting the efficiency of the transfer process. Also, the increase in oil viscosity by weathering, emulsification, and reduced temperatures may restrict the use of pumping.

Ice Removal--

In some extreme cases the removal of contaminated ice has been used in oil-spill cleanup. In general, the amount of oil in the ice is very small, and the volume of ice required to recover even a slight amount of oil would be very large. This technique is often extremely costly and may result in more damage to the environment than just leaving the oil to weather naturally. However, in some cases ice removal may be a practical solution for cleanup. Before using this technique, it is important to estimate the amount of oil contained in the ice and the volume of ice being considered for removal. Equipment availability, cost, and manpower requirements should be estimated. In addition, potential damage by heavy equipment, secondary spillage, and oil/ice removal facilities should be weighed against treating the oil in situ by other means.

Nonmechanical Recovery

Nonmechanical techniques often are viable in cold regions because of environmental restrictions, logistics, and limits in equipment and skilled manpower.

In-Situ Burning--

In-situ burning has been proven to be one of the most important cold-region spill response options. The remoteness of many cold-region spill sites has resulted in the smoke posing less of a threat to nearby communities. Cold temperatures keep the oil viscous, the slick adequately thick, and restrict the escape of volatiles, which greatly aids combustion. Also, the containment and absorption by ice and snow greatly helps in-situ burning of oil. The burning of oil in between ice floes and on the ice surface will likely serve as an important oil pollution countermeasure in the response to cold-region spills.

The basic requirements for slick ignition are raising fuel surface temperature to its fire point, having enough vapors present to ignite, and having sufficient slick thickness and oxygen. Insufficient oxygen allows unburned fuel particles and soot to escape; thus levels of soot can be controlled by increasing the flow of air by fans or blowers. On the other hand, if excess oxygen is present, it cannot react in the flames and acts as a coolant.

Burning an oil slick on cold, open water can be considered the most difficult situation for in-situ burning. The oil slick must be thick enough to support combustion, more than 5 mm (0.2 in) (NORCOR, 1975). In arctic field trials, unconfined slick thickness was observed to be typically 1 to 2 mm (0.04 to 0.08 in). Conventional booms are available to thicken slicks, but they are not sufficiently fireproof to avoid being consumed by intense flames during spill combustion.

Wicks can help sustain combustion in fluids that would not burn otherwise. The wick provides many tiny pores through which fuel rises from the oil slick for easier preheating, vaporization and ignition. Wicks can consist of inexpensive materials, such as straw, peat moss, asbestos fibers, and/or various cinder-like materials, or commercial preparations such as Cab-O-Sil, Aerosil, and Fibreperl. Wicks should be used where the oil is thin and/or unconfined, and in waves. Wicked slicks burn much longer and with less smoke than non-wicked slicks. Unfortunately, some residues from burning slicks with promoters (such as woodchips and straw) do sink. Commercial wicking materials such as Fibreperl are toxic, and should be handled by personnel wearing gloves and dust masks.

The ignitability of the slick is affected by oil characteristics and wind Heavy oils, such as Bunker C, have few volatile materials and require a high fire point. Hydrocarbon evaporation and the formation of emulsions also raise the fire point, but fresh oil slicks emulsified with up to 50% water can be ignited (Twardus, 1979). Though aging raises the fire point, many types of crude oil can be burned after being aged for intervals of up to 4 weeks. The wind speed limiting ignition for directly exposed fuels was found to be 4.5 m/s (14.8 ft/s). However, even with a narrow obstruction at the upstream edge, the flame is able to withstand much higher wind speeds, and the burning rate will increase. It was found that a projection 3.2 mm (0.13 in) above the slick raised the limiting wind velocity to 24 m/s (78.7 ft/s).

The slick can be ignited by oily rags, flame-throwers, or brush-burners. Once oil begins to burn, it will spread, burning at a fairly constant rate until the flame goes out. Large area fires will burn about 1.5 mm/min (0.6 in/min) of oil from the surface of the spill and burn out when the thickness decreases below 5 mm (0.2 in).

Unconfined oil slicks may be burned when the concentration of ice floes is high enough. Ice serves as an effective containment mechanism, especially for oil of high viscosity. Slicks of heavy oils probably will exceed the required 5-mm (0.2-in) thickness when ice concentrations are 90% or higher. Low-viscosity oils, such as diesel fuel, require ice concentrations of greater than 95% to provide adequate confinement. For thin, slush ice conditions, there was not enough advantage in using wicks over burning the oil alone. However, for thick slush ice conditions, wicking agents increase the fraction of oil burned (Tam, 1979).

Oil that has pooled on solid ice can be burned easily. Such oil will settle into the crevices and depressions to form thickened lenses that can be burned without wicking agents if over 5 mm (0.2 in) thick. Wicking agents can extend burning down to 2 mm (0.08 in) oil thickness (Peterson et al., 1975 b). If the ice is rough the raised edges of the ice serve to block the wind, lessening the chance of the flame being blown out. Oil that has spilled underneath the ice and that rises, though slowly, to the surface during ice decay can be burned since it has undergone little weathering while underneath the ice. Despite some of the problems encountered, in-situ burning on solid ice has proven to be a successful spill countermeasure.

One of the main concerns of in-situ burning is the amount of soot and smoke released from the fire. The principal concern is the high soot concentration in the immediate vicinity of the fires. Human entry into such areas should be avoided, as there is doubt about the effects of polynuclear-aromatic hydrocarbons and metals that will be present in the soot. It is prudent to minimize the exposure of personnel and communities to these substances by careful planning of the burning operation, using short-range weather forecasts.

Sorbents--

Desirable sorbents are floating substances (inorganic, natural organic, polymeric) that soak up or absorb the oil or present a surface for the oil to cling or adhere to. In cold regions some sorbents are effective on very thin slicks of oil, some too thin for mechanical recovery or in-situ burning. Sorbents can also be used as a second-stage response after recovery devices have removed most of the oil. Some adhesive sorbents are effective with highly viscous oil.

A number of disadvantages may be associated with the use of sorbents. No system for a large-scale mechanical recovery of sorbents exists. Use of sorbents may involve high cost, including the cost of acquisition, labor, transportation, storage, application, recovery, and disposal. Recovery of spent sorbent is difficult, except in calm seas, and may not be feasible in an ice environment. Some sorbents may interfere with the operation of other recovery devices. The recovered oil-soaked sorbent may present a disposal problem, though in some cases it may be possible to use the recovered product as fuel. Some sorbents sink when saturated, making the product unrecoverable.

Dispersants--

Dispersants are generally most effective when applied to unweathered oil slicks in relatively warm water, and normally must be applied in a ratio of about 1 part dispersant to 5 to 10 parts oil, depending on the type of oil and its viscosity, the efficiency of the dispersant, and the available mixing energy. In cold regions, the amount of dispersant required to emulsify a given slick is greater. As temperature drops, the oil viscosity increases and the quality of dispersant needed also increases (Mackay et al., 1977). In laboratory tests it was found that decreasing the temperature from 20°C to 10°C caused a factor of 2 decrease in the quantity of oil dispersed. Similarly, dispersion dropped by a factor of 3 as the temperature dropped from 20°C to 5°C. Though these test results are preliminary, they do indicate that dispersants have reduced effectiveness at lower temperatures.

The use of chemical dispersants is a highly controversial issue that has received considerable attention from government regulatory agencies that have specified acceptable dispersants. Their use is usually considered a last resort in most cleanup programs, since dispersion of oil throughout the water column may harm a far greater number and variety of organisms than would be affected when the oil is concentrated on the surface. Use of dispersants may be considered in open seas, where booms and skimmers are ineffective and where the oil slick is threatening areas of major biological importance.

The subject is fully discussed in the manual on dispersants (U.S. Environmental Protection Agency, 1981).

Biodegradation--

The ability of microorganisms to degrade petroleum is a geographically common characteristic. Over 200 hydrocarbon-utilizing microbes have been identified wherever careful attempts have been made to isolate these organisms, though numbers are greater in areas where oil has been previously added (Zo Bell, 1973a; Karrick, 1977).

Because the marine bacteria are predominantly cold-adapted organisms that grow fairly rapidly at temperatures near the freezing point (psychrophilic), it is not unexpected that microbial degradation of petroleum hydrocarbons can occur in cold regions. Kinney et al. (1969) found that biodegradation was more important than physical flushing in removing hydrocarbons from Cook Inlet, estimating biodegradation of crude oil to be essentially complete in 1 to 2 months.

Temperature may be the major factor influencing microbial degradation rates in cold regions; it suppresses growth and metabolic rates of the microbes involved, resulting in lowered rates of degradation (Atlas, 1977). Degradation can also be influenced by an inhibition of growth resulting from an increased retention of toxic components in the petroleum at the lower temperatures. A direct relationship has been demonstrated (Zo Bell, 1973b) between temperature and microbial degradation in samples collected from oil-polluted waters, oil-soaked soil, and tundra of the North Alaska Slope and oil seeps along the Colville River. Reproduction rates at 8°C were twice as fast as rates at -1.1°C; rates were almost the same at 4°C and -1.1°C. Microscopic observations indicated that the tendency for the lower temperature to retard reproduction was offset, in part, by the beneficial aspects of the surface substrate provided by the slush ice at -1.1°C.

Nitrogen and phosphorous (available as NO_2, NO_3, NH_4, and PO_4) have been shown to be limiting factors to both rates and extents of petroleum hydrocarbon degradation (Atlas, 1977; Bartha and Atlas, 1973; Reisfield, 1972). These nutrients would probably be more commonly limiting in the open oceans than in inshore waters. In Prudhoe Bay, Alaska, small, contained oil slicks were supplemented with an oleophilic fertilizer that contained nitrogen and phosphorus. The addition of the nutrients enhanced the rate of biodegradation. Oxygen is also critical to the degradation of oil, though it is probably not limiting in surface and near-surface waters. However, incorporation of the oil into anoxic sediments can cause the hydrocarbons to persist for long periods of time (Hunt et al., 1969).

COASTAL AND TERRESTRIAL

Oil spills on land are of two types: coastal spills originating in open water and later washed ashore, and terrestrial spills originating from pipeline failures, storage ruptures, tank truck accidents, etc. Criteria important in the selection of proper response equipment for coastal and terrestrial areas include oil properties and volume, logistics, and environmental conditions, such as composition of sediment, slope, and the season. During winter the presence of ice and snow minimizes not only the surface area covered, but also the penetration of oil into the sediment. Frozen ground provides a solid surface for the use of heavy mechanical equipment to remove oil. When oil is spilled on permafrost areas or marshes during the warmer months, heavy equipment should not be used. Heavy vehicles compact the insulating active layer of permafrost and cause an eventual melting (thermokarsting) or damage the root system of marsh vegetation. Several mechanical recovery devices commonly used for coastal and terrestrial spill response include heavy construction equipment, steam cleaning, sand blasting, hydraulic flushing, mechanical beach cleaners, and groundwater skimming and suction. Nonmechanical recovery devices include in-situ burning, manual removal, sorbents, and biodegradation.

Mechanical Recovery

In all mechanical recovery operations it is critical to remove as little uncontaminated sediment as possible. Where large volumes of sediment are removed, it is advisable, in most cases, to replace that sediment to prevent adverse alterations of the beach or terrain equilibrium. Oil removal from beaches should be carried out as soon as possible, provided there is no danger of recontamination. Removal of the top layer of contaminated sediment from large areas is best accomplished by heavy construction equipment. This equipment includes motorized graders, elevating scrapers, front-end loaders, bulldozers, backhoes, drag lines, and clam shells. Use of this equipment has been described in detail by Woodward-Clyde (1979).

Steam cleaning equipment uses a high-pressure steam jet that will remove oil from almost any surface. It drives oil off one surface onto another, requiring that precautions be taken to avoid recontamination of previously unaffected areas. It is used as a means for removing oil coatings from boulders, rocks, and man-made structures. However, this method is harmful to flora and fauna, as well as being expensive and is not usually recommended for surfaces that support living plants or animals. Sand blasting uses sand applied to surfaces of man-made structures at high velocity to remove oil from the substrate by the abrasive action of the sand. The accumulation of sand, oil, and surface material in the area near the operation must be removed and transported to a disposal area.

Hydraulic flushing includes both high-pressure and low-pressure dispersion. High-pressure methods can be used to wash oil from coarse sediment, rock surfaces, or man-made structures. This method uses high-pressure jets of water (often heated), and should be used only by trained personnel who can properly control the powerful jets. Low-pressure hydraulic dispersion is a biologically preferred method and can be used in marshes and for flushing out oil-contaminated sediments. This method is not applicable to sand beaches as the water would wash away the sediments, and on coarse sediment beaches it would lead to greater penetration of the oil. Under no circumstances should hydraulic dispersion be used to clean unconsolidated cliffs because this would result in undercutting of the cliff or slumping. The runoff from the flushing operation must be properly channeled and collected. Test flushing should be done in each situation to determine the suitability of this technique. Soaking the substrate will generally float oil off the surface without any adverse effects. The flushing should begin at the highest contaminated point and work downslope.

Mechanical beach cleaners have proven to be a fast and efficient method of cleaning sand or gravel beaches lightly contaminated with high-viscosity oil. The majority of beach cleaners are towed behind a tractor or front-end loader. A blade or rotating drum fitted with blades scoops up the top layer of sand, debris, and viscous oil. It places the collected debris on an incline wire mesh conveyor that moves the contaminated material up while allowing the clean sand to fall through. The remaining oil and debris are dumped into a refuse container mounted on the rear of the conveyor belt. The conveyor may be a wire mesh screen, a series of bars, or a rotating conical screen. These units typically travel at a speed of 3 to 10 km/hr (1.9-6.2 mi/hr.

The spined drum (Caltrop machine) beach cleanup concept developed and tested by Environment Canada is useful for recovering high-viscosity oils spilled on sandy beaches (Russell et al., 1979; Blackall, 1979). The spined drum has viscous oil or emulsions adhere to it as it is rolled over the spill, and a rotating brush removes the oil into a collection bin.

Nonmechanical Recovery

In-situ burning is used on coastal and terrestrial substrates and vegetation where sufficient quantities of oil of proper volatility have collected. The mechanisms of burning and the use of wicking agents have been described in the section on aquatic recovery. The feasibility of burning should be determined by a test ignition away from the actual spill site. Once burnability has been demonstrated, permits must be obtained from appropriate regulatory agencies such as the EPA, state fish and wildlife agencies, and local air pollution agencies. Consideration must be given to the potential environmental damages resulting from burning. Concern about public and wildlife safety and potential air pollution strongly affect the granting of permits.

Oil can be burned more successfully if it is contained on an ice surface, and in this case the residues are relatively easy to remove. Oil that is mixed with snow can also be burned. Oil in marshes can be successfully burned during cold temperatures, but great care must be taken that the root systems of the vegetation are not damaged. Controlled burning is frequently used in marsh management (Castle, 1978). It should be noted that when oil is burned on sediments an undesirable, heavy, difficult to remove residue may remain, and the smoke from burning can be undesirable in heavily populated areas. Also, the oil not yet burned will heat up and can penetrate more deeply into the sediments.

Manual removal of oil is in order for small amounts of oil spilled or in areas inaccessible to machinery. It is labor-intensive and can therefore be expensive. This method has been an integral part of cleanup programs in the past and has been found to be effective in restoring contaminated shorelines and terrestrial areas. Sorbents can be used on land as well as in water. They are most effective on shorelines when they are distributed on the beach before the arrival of the oil slick. Wave energy mixes the oil and sorbents, and sorbents also limit oil penetration into sediments.

The primary method of recovering oil from groundwater by skimming and suction is to create a local cone of depression in the water table by drilling a well. The well interrupts the water flow, so that the withdrawal of water creates a depression. Oil floating on the water table within the depression is prevented from migrating farther and can be pumped off for disposal.

A second method involves constructing a ditch across the entire front of the migrating body of oil and below the top of the water table. The ditch should be at least 0.91 or 1.22 m (3 or 4 ft) below the water table, and the pumping capacity should be great enough to keep the water drawn down to the bottom of the ditch. The ditch must be wide enough to accommodate the necessary pumps or other removal devices. Ditches deeper than 1.8 to 2.4 m (5.9 to 7.9 ft) are usually impractical; the limitation is imposed by the need to avoid caving of the ditch walls. As the oil floats across the ditch, it is skimmed off the surface of the water. If the ditch is to be a collection point for skimming, its downstream wall should be lined with an impermeable material, such as polyethylene film. The film will block floating oil but permit water to pass below. Skimming must be continuous, or collected oil will tend to move to the ends of the ditch and pass around the barrier.

Ditches are usually less effective than wells for creating a depression in the water table. However, ditches produce much less fluid to be handled at the surface and with a small spill the ditch method may be preferable.

SECTION 8

TEMPORARY STORAGE

Temporary storage is often required as a buffer between recovery and disposal. In addition, smaller containers may be useful when ferrying oil from a skimmer to a tanker or a holding unit of larger capacity. Actions taken to store the recovered product will depend largely on the following factors (Peterson, et al., 1975b).

1. Aquatic or terrain conditions,
2. Transportation, access, and logistics,
3. Availability of storage systems,
4. Presence of debris (including snow and ice),
5. Properties of the recovered product (for example, viscosity and density),
6. Ecological damage caused by storage,
7. Cost of storage,
8. Weather conditions,
9. Storage capacity required,
10. Time to place storage in operation,
11. Durability or reuse possibility of storage, and
12. Personnel safety.

Storage alternatives are classified in terms of location: aquatic or land-based storage. These storage classifications are subdivided according to transportation access (by water, land, and air) and logistics requirements for the storage operation. The use of natural features to store spilled oil is also considered.

AQUATIC-BASED STORAGE

The most desirable aquatic-based storage are tankers, barges, and ships. This is true particularly in cold regions where shifting ice could easily

easily puncture inflatable containers, though air-transportable, flexible containers may be useful on solid ice. When these portable means of storage are not available, the use of natural features may prove useful.

Ship-Dependent Storage

Tankers provide an excellent means of temporary storage for large oil spills. Conventional tankers can be used in limited ice conditions. Icebreaking tankers are being developed and potentially could be used for heavier ice conditions. A wide variety of sizes are available, ranging from an oil-holding capacity of one million gallons up to the multimillion-gallon capacity of a supertanker. The problems with ship storage include the distance that an available tanker might be from the spill site, local ice conditions, local water depths, and the tanker's ability to transit through ice at a fast enough speed to be at the spill site when needed.

Tank barges may be used in limited ice conditions. They normally range in size from approximately 757 to 15,140 m^3 (200,000 to 4 million gal). A typical small barge has a 1125 m^3 (300,000-gal) capacity. These barges have the potential for use as work platforms. The cargo heating elements installed on some barges can be used for heating the recovered oil/water/ice mixtures and separating the oil and water. Problems associated with using barges are the same as those for tankers.

Locally available ships can afford excellent temporary storage, but they are generally limited to handling liquid products and have smaller storage capacity, usually less than 151 m^3 (40,000 gal). Portable tanks can be hoisted on board these ships. Fishing tenders are capable of holding several thousand barrels of recovered oil in holding tanks below the deck. Immediate storage in these vessels is advisable only if other satisfactory alternatives are lacking. Disadvantages in using locally available vessels include the need for secondary cleanup or restoration of the vessels. Also, ice conditions may severely restrict their use.

Air-Deployable Aquatic Storage

Collapsible floating containers may have some use as temporary storage units in cold regions. These containers are flexible and are usually constructed of synthetic rubber and nylon fabric. They collapse into air-transportable size for quick spill response. After being filled, they can be towed from the spill site by tugs. These containers are only effective for collecting oil that is pumpable and without debris. Oil may be pumpable during initial storage, but cooler temperatures may increase viscosity, making secondary transfer from the container difficult. Abrasion by ice needs to be minimized. One way to do this is to place the container on a solid ice platform or on a large ice floe until other storage systems become available. Problems with using the collapsible containers are that they are difficult to maneuver in heavy seas, and they are vulnerable to puncture.

Another type of air-deployable storage is the donut (Figure 27), and it can also be used as a floating oil/water separator. It is a modified version of the U.S. Navy oil disposal raft. The donut floats partially submerged

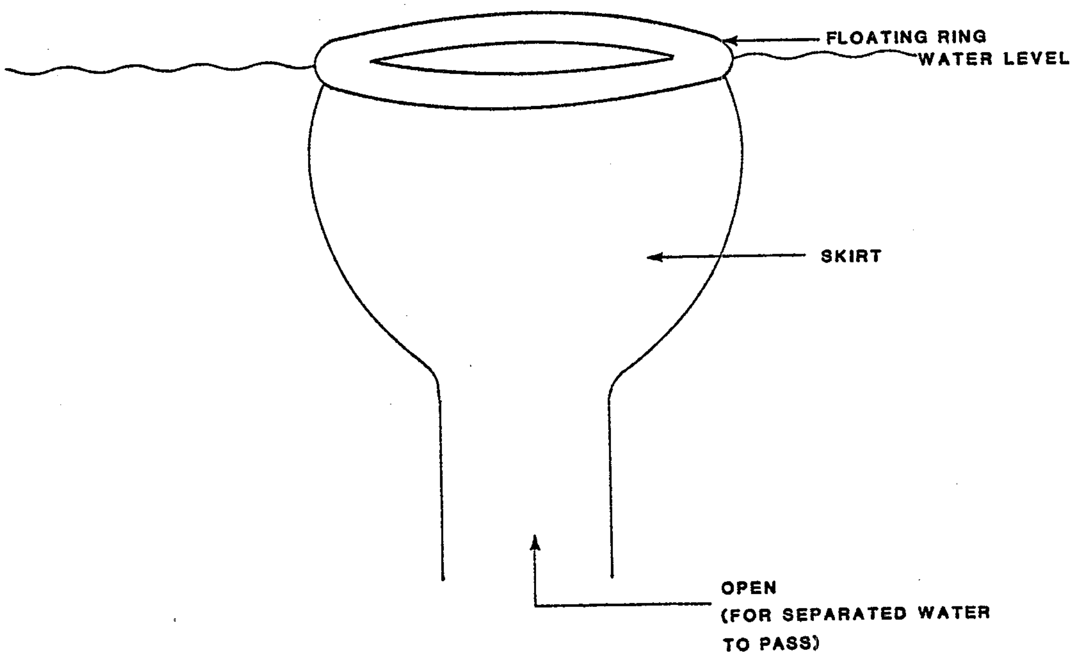


Figure 27. Donut storage container and oil/water separator.

while an oil/water mixture is loaded. The oil and water separate, as a result of gravity, and the water is forced out the bottom. The remaining oil is contained in the donut-shaped raft. The donut is not considered usable in broken ice; however, it may have some application for storing oil in solid ice. A hole could be drilled through the ice, and the oil/water separator could be floated in the hole.

Natural Features for Aquatic Storage

Natural aquatic features, such as lakes, lagoons, and solid ice, can provide readily available and effective temporary storage for recovered oil. The use of these features is recommended only in cases in which oil cannot be burned *in situ* or stored in portable containers. Large spills will severely strain the utility of all portable storage systems. The use of natural features may be necessary to complement portable systems for these large spills when the oil cannot be burned. Using natural features for storage can be justified only if the potential ecological threat associated with not providing storage outweighs the local damage threat from the use of natural storage.

Lakes or lagoons can serve as effective containers. The petroleum companies at Prudhoe Bay have developed contingency plans to use local thaw lakes for emergency oil storage (Peterson, et al., 1975b). The procedures for use vary with the seasons. During the summer, the lake is pumped out with high-capacity transfer pumps and the oil is subsequently pumped in. During spring runoff, secondary containment barriers or dikes are constructed to prevent loss of the oil. In the winter, the bottom of the deeper lakes remains unfrozen, so the water is pumped out and replaced with recovered oil.

Shorefast ice can also provide an effective means of containment. Oil could be transferred onto the ice surface, where it would be retained by natural or man-made barriers. A storage pond could be constructed on the ice by building a containment wall of ice and snow. If temperatures are below freezing, the wall could then be sprayed with water to provide a solid ice lining. Several problems, however, occur when using this technique. The temperature of oil stored on ice may be reduced to a value well below its pour point. Thus, immediate storage may be successful, but ultimate disposal could be made more difficult. Secondly, oil may be quickly mixed with blowing snow, also making disposal more difficult. In addition, oil stored on ice may penetrate through the brine channels of decaying ice, further complicating disposal.

LAND-BASED STORAGE

The most desirable land-based storage systems are those easily transported to the spill site by roads. When the site is not accessible by road, storage units probably will be air-transported. When portable temporary storage is not available, the use of natural features is the final alternative.

Road-Dependent Storage

Tank trucks and vacuum trucks are often used for temporary storage. Tank trucks, used to transport petroleum products on roads, typically have a capacity of 3.8 to 24.6 m^3 (1000 to 6500 gal). Vacuum trucks typically have holding capacities varying from 3.8 to 17 m^3 (1000 to 4500 gal).

A wide variety of land-based vehicles can be used with portable storage containers. For example, flat-bed trucks could be used to transport collapsible pillow tanks. Dump trucks lined with an oil-impermeable barrier can be an effective means of removing oil-contaminated debris, snow, and ice. Drums with a capacity of 208 liters (55 gal) mounted on trucks may also prove useful for small spills.

Other types of storage, such as in sled-mounted tanks, would be useful on snow or ice roads. Various land transportation systems have been developed for use on ice, snow, and tundra, and many are capable of transporting pillow-type containers.

Air-Deployable Land Storage

Local terrain will influence the choice of air-deployable storage containers. Permafrost is common throughout many cold regions. Instabilities in ground footing occur in locations where soil contains moisture, such as typical tundra. Containers placed on moist terrain and on permafrost are susceptible to shifting during the thaw cycle of the active layer. Two approaches have historically been used to ensure sound footing for structures in permafrost regions: (1) destroy the permafrost, and (2) insulate the surface layer to prevent thawing. Neither of these alternatives appear feasible for temporary storage because of the emergency nature of spill response. A third approach for placement of temporary struc tures would be to provide a device capable of floating or shifting as the active layer thaws (Peterson, et al., 1975b). Therefore, flexible tanks are preferred over the rigid-wall type.

Pillow tanks (or bladder bags) are considered the most satisfactory air-transportable storage for permafrost areas. Pillow tanks can be used also for storage of oil on large ice floes or shorefast ice. These tanks are currently available in a variety of shapes (generally square or rectangular) and capacities that range from 0.45 to 37.9 m^3 (120 to 10,000 gal) for use in cold climates. Pillow tanks can be folded into small, relatively light bundles that are easily transported by fixed-wing aircraft, helicopters, or trucks. These tanks, when filled, can be easily moved by a variety of vehicles such as flat-bed trucks or sleds. Storage containers sized up to 1.89 m^3 (500 gal) are transportable by medium-lift helicopters that have 2265 kg (5000 lb) capacity for slug loads (Logan, et al., 1975). Pillows are commonly used for fuel storage, both in the Arctic and Antarctic, though their outer surfaces may chafe or puncture. Also, these bags are not capable of handling non-pumpable oil and debris.

Open-topped containers are an excellent means of storing highly viscous oil and debris. The open tops allow pumping by several hoses at once. Prefabricated open-topped containers are available that have an inflatable ring around the top edge that rises as the oil level increases. Portable pools, such as commercial aboveground swimming pools, also are an economical means for storing small volumes of oil. These pools have the advantage of low cost, availability, transportability, and the capability of storing debris. Both types of open-top containers can sustain some shifting with permafrost thaw, but they are not as safe as closed-pillow tanks. A pillow-type cover, with good seals, could be used on open-topped tanks to protect the stored product from rain and snow.

Some spill situations may require containers that are lightweight, rugged, combustible, and capable of being handled both by personnel and light equipment. The most suitable containers identified for handling small quantities of light debris are portable shipping containers, developed primarily for air cargo (Peterson, et al., 1975b). Thecontainers are mounted on standard pallets and consist of knockdown waxed cardboard sides and a lid. The dimensions are approximately 1.2 m x 1.2 m x 1.2 m. A suitable plastic liner would be required to prevent leakage of liquids from the container.

Conventional steel tanks are available in a wide range of sizes. They can be heated for the separation of oil and snow mixtures and possibly used for disposal by burning. However, they are considerably heavier and bulkier than flexible storage containers, and may tip as a result of ground thaw.

Natural Land Features for Storage

Storage in natural features is advisable only if the potential ecological threat of the uncontrolled spill far outweighs the localized damage threat from the storage technique.

Lagoon pits and containment dikes have been used on land in the Arctic as a safety measure to contain oil spills from tank farms. In general, there is no standard approach to the construction of these pits; however, it has been recommended that, because of the relative scarcity of clays or other permeable soils in the north, a synthetic impermeable barrier should be used. The plastics, used as impermeable films, include polyvinyl chloride (PVC), oil PVC, polyethylene (PE), chlorinated polyethylene (CPE), chlorosulphated polythene (COSE), urethane, and butyl rubber. The edges of the sheet must be weighted with stones or earth to prevent wind damage.

Snow could be used for the support walls of a storage pit. If permafrost is present, the active layer should not be removed. However, the permafrost ice lens could serve as a good impermeable base if necessary. Water can be sprayed to form an ice liner if ambient temperatures are cold enough. If firm clay soil exists, storage without liners may be possible, but extra protection is still desirable. If a plastic sheet is not used, a flat-bottomed pit should be excavated and a layer of water maintained across the base to help keep the oil from the substrate.

SECTION 9

PUMPING SYSTEMS

Pumping systems are used to drain skimmers, to move collected oil to temporary storage and from temporary storage to a disposal facility, and to recover oil directly from locations where it has pooled.

PUMPS

For use in cold regions, pumps should have the following characteristics (Purves and Solsberg, 1978):

1. Suction-lift and self-prime with high-viscosity fluids,
2. Tolerance to debris, including ice and snow,
3. Importing low shear to the pumped fluid,
4. Ease of handling and repair with gloves, and
5. Reliability at below-freezing temperatures.

Suction-lift and self-prime with high-viscosity fluids is of particular importance in cold regions, where heavy oil spills are common. Each step of the recovered oil transfer process -- from skimmer to temporary storage to disposal facility -- normally involves raising the fluid volume 2 to 6 m (6.6 to 19.7 ft), typical for the freeboard of a vessel or the height of a dock at low tide. The first step of transfer, from a skimmer to temporary storage, involves taking suction near the water level. Unless the pump is mounted below the waterline, the pump must provide suction-lift. Also, typical nearshore skimmers are very small vessels with low stability, storing about 1 m^3 (264 gal). Any small disturbance can cause the pump to lose prime. Therefore, a pump should be capable of moving No. 6 fuel oil (150,000 sSU viscosity at 0°C) at 190 liters per minute (50 gal per minute) through 2 to 6 m (6.6 to 19.7 ft) head, and it should be self-priming. If a pump does not meet this criterion, it will be unsuitable in many common spill applications.

Most recovered oil contains solid debris, particularly high concentrations of ice of every shape and size. Oil/snow mixtures, of approximately 70% snow, may also require transfer. An ability to pass solids, such as ice chips and slurries of oil and snow, is thus an important qualification. This reqirement is commonly met in pumps used in construction applications to dry out excavations. These pumps routinely pass stones, mud, and ice without clogging or breaking down.

Low shear of the pumped fluid is important in reducing emulsification of oil and water, the latter often present in large quantity. Stable emulsions of 50% or more water could form, adding to storage volume and creating disposal problems. Not all spilled materials form stable emulsions easily, but this possibility should be considered in pump selection. Studies of the emulsion-forming processes within a pump (Harvey et al., 1973; Fruman and Sundaram, 1974) found that centrifugal pumps, with their vigorous acceleration of fluid, generally emulsify more than positive displacement pumps.

Ease of handling and repair is also a desired quality. Personnel wearing mittens should be able to accomplish common manipulations (such as starting and moving pumps) and routine maintenance (for example, changing oil and air filters).

Reliability of operation at below-freezing temperatures is essential. Pumps with impellers could freeze in place, and the motor might not have sufficient torque to start the pump. The pump body could become brittle and be subject to fracture upon impact. Synthetic rubber seals might crack and leak at cold temperatures. Lubricating grease, normally used in temperate climates, might solidify. Therefore, if possible, inquiries should be made to the manufacturer to find out if their pump has been successfully used in cold climates.

Pumps commonly used for oil-spill response fit into two general classes: centrifugal pumps and positive displacement pumps for comparable lift capacity. Centrifugal pumps are typically simpler and less expensive, with few moving parts or precision clearances. Unfortunately, the practical viscosity limits are much lower in most centrifugal pumps than positive displacement pumps. Viscosity affects the operation of the centrifugal pump by reducing the velocity of the oil flow through the pump. Centrifugal pumps are widely used in the construction industry for drying out excavations, and they are usually driven by diesel or gasoline engines.

Positive displacement pumps are often precision designs for fixed installation in chemical processes. Unlike centrifugal pumps, they are generally self-priming and produce a flow not severely affected by pressure variations. The higher pressure capability of positive displacement pumps is useful in overcoming the frictional losses in pipes due to high-viscosity fluids. The flow capacity of a positive displacement pump is restricted by the ability of the fluid to fill the pump's internal cavities, so its speed is usually reduced as fluid viscosity increases. Most positive displacement pumps have a high viscosity range, far greater than that of centrifugal pumps. Positive displacement pumps exert less shear on the fluid than centrifugal designs and thus are less likely to form emulsion when pumping oil/water mixtures (Harvey et al., 1973; Fruman and Sundaram, 1974). Unfortunately, many types are designed for pumping clean fluids, and their valves and precision clearances will not tolerate suspended solids.

Laboratory and field tests and engineering analyses have been performed on several available pumps to evaluate their suitability for cold-region oil-spill response. Information on seven pumps for arctic use reportedly capable of handling viscous oil and oil/water mixtures are listed in Table 16.

TABLE 16. PUMPS FOR HANDLING HIGHLY VISCOUS OILS*

Pump name	Max. viscosity it can pump	Max. capacity at 250,000 SSU	Type of pump	Remarks
	SSU	m^3/h		
Moyno	5,000,000	13.63	Screw conveyor	Can handle solid particles up to 25 mm. Hopper intake and auger.
Sier-Bath	5,000,000 30,000,000 also available	20.45	Double-screw external gear and bearing	Hopper-type intake and hard-faced screws available. Pumps cold oil at 300,000 SSU. Unexcelled for Bunker C.
Roto-King (Viking)	2,000,000 Standard up to 250,000	45.43 45 kw required to produce 345 kPa	Internal gear rotary	332 Series
Waukesha	700,000	34.08	Twin-blade metal rotor or Dualobe rubber rotor	Abrasive not recommended.
Blackmer	Quoted no limit. Standard up to 100,000		Vane	Handles abrasive such as slurries. Easy to replace worn parts. Relatively small capacity.
Spate	10,000	11.36	Induced flow	Inexpensive, lightweight; portable proven reliability in spill situations.
Megator	10,000	13.63	Sliding shoe	Inexpensive; lightweight portable

* Logan et al., 1975.

McLaren (1978) investigated several pumps for arctic pollution response and found the Moyno 1L10H, Roper 71228NL, Midland 1600/630EH, and Offshore Devices pumps to have the best designs. Purves and Solsberg (1978) conducted laboratory tests on 11 pumps and found the Megator L150 and Gorman Rupp 3D-BKND pumps to be best suited for cold-region spill cleanup. Mittleman (1978) conducted tests on five hydraulically-powered, submersible pumps for transferring cold viscous oil at high rates for offloading stricken vessels, but did not evaluate their ability to pass debris (Table 17). The Prosser pump was chosen for its design specifications. Presently, the Framo TK-5, a new pump design, is being evaluated and shows the best potential of all the pumps for offloading viscous oil. Pumps listed as having the highest performance will not necessarily perform trouble-free in the cold regions. Modifications to many of these pump designs will further enhance their cold-region performance.

PRIME MOVERS AND HOSES

The prime mover is the power source for the pumping system. It is generally a gasoline or diesel engine, or gas turbine. In addition to the usual space, weight, and power considerations, the prime mover must be designed or retrofitted for cold-region operation.

As an alternative to starting the prime mover at extremely cold temperatures, it is a common practice in the Arctic to enclose the engine in a heated shelter or to use a portable heater to bring the engine up to a higher temperature before attempting to start it. Once started, the engine may be kept running as long as it is needed.

Additional factors and precautions apply to cold-weather operation. These include the use of special seals, gaskets, gauges, starter valves, fan belts, and fluids designed for cold regions.

Transfer hoses must be lightweight and flexible to allow deployment and recovery with a minimum of manpower and equipment. A 7.6-cm (3.0-in.) diameter hose probably would provide the combination of flexibility and ease of handling needed for cold-region spill countermeasures (Logan et al., 1975). A hose of this diameter is capable (with 30 m [98.4 ft] of pump discharge head) of transferring oil of 60 sSU viscosity at the rate of 310 liters per minute (82 gpm) for 425 m (1394 ft). Under similar conditions, 200 sSU oil can be pumped for 90 m (295 ft). Technical information on transfer hoses, suitable for use at low temperatures, is provided in Table 18 (Logan et al., 1975).

Brittleness at low temperatures may result in the cracking of many standard hoses. It is expected that this will occur when unrolling and flexing the hose before pumping. Therefore, special hose material should be used, specifically designed for cold-region use. Standard couplings and gaskets on hoses may fail, and many standard connections may prove difficult to manipulate with mittens.

During response operations, the oil/water/ice mixtures may freeze and clog the hose if there is a considerable distance between the pump and storage

TABLE 17. HYDRAULICALLY-POWERED SUBMERSIBLE PUMPS FOR TRANSFERRING VISCOUS OIL*

Make	Model	Type
Prosser	7-13185-20 with #1, 2, 3 impellers	Centrifugal pump
Byron-Jackson	8 in. HG-H	Two-stage vertical turbine pump
Framo	TK6	Centrifugal pump
Midland-Bornemann	EH1600-630	Progressive cavity pump
Moyno	IL12	Progressive cavity pump

* Mittleman, 1978.

TABLE 18. FLEXIBLE OIL TRANSFER HOSE*

Size (mm)	Approx OD (mm)	Wt per m (kg)	Working pressure (kPa)	Bending radius (mm)
31.8	48.5	1.54	1035	15
38.0	29.5	1.77	1035	203
50.5	42.0	2.23	1035	229
63.5	82.5	2.95	1035	305
76.2	95.25	3.77	1035	308
101.6	120.6	5.15	1035	457
127.0	146.0	6.92	690	760
152.4	171.5	8.63	517	914
203.2	225.4	13.09	345	1220

* Logan et al., 1975.

container, as occurred at the 1977 Buzzards Bay oil spill (Deslauriers et al., 1977). Hoses extending 400 m (1312 ft) from the vacuum trucks on shore to pools on the ice were clogged by small ice chunks, sucked from the pool, and water freezing in the lines.

For thawing the clogged hoses were disconnected and attached to the exhaust of trucks, a move that was marginally successful. It was found that if little air was taken into the hoses, the freezing problem was minimized. Other methods have been proposed to reduce clogging, such as insulation. Mittleman (1978) proposed wrapping heating coils around the hose, not only to prevent clogging but also to form a low-viscosity oil film on the hose wall, greatly reducing the drag of viscous oil.

SECTION 10

DISPOSAL

Techniques for the disposal of recovered oil and debris vary widely, but they can be categorized as incineration, salvage, and land disposal. Factors that help determine the most suitable technique for a specific response include:

1. Logistics,

2. Equipment availability,

3. Properties of the recovered product (for example, volatility and viscosity),

4. Spill volume,

5. Amount and type of debris, and

6. Impact of disposal techniques on the environment.

Often, disposal techniques cannot be pre-planned, and the OSC should be familiar with the available disposal alternatives. For example, if the recovered product is mixed with snow and other debris, mechanical incineration at the spill site, by open-pit or rotary kiln burners, may be suitable. If a spill occurs near an oil well or pipeline and the recovered product is in a liquid state, salvage techniques such as reinjection into the pipeline may provide the best disposal means. Other situations, such as a large spill that occurs in a remote area with a high percentage of oil-contaminated soil and gravel, may require land disposal techniques, such as land cultivation or burial.

Some oil disposal techniques, such as <u>in situ</u> burning, chemical treatment, and biodegradation, do not involve the recovery step. These techniques are described in Section 7 of this report. This section covers only disposal of recovered oil.

INCINERATION

Mechanical incineration provides a viable and safe method of eliminating recovered oil. Controlled incineration greatly reduces smoke, as burning takes place at a very high temperature in a combustion chamber. Because the burning process is efficient, very little residual material is left after incineration, and what little is left may be disposed of at a landfill site.

Several types of incinerators have been designed for disposal of recovered oil and debris. They include flare burners, open-pit incinerators, rotary kilns, and stoker-type incinerators.

Each type of incinerator is designed to dispose of certain recoverable materials and volumes. For burning large amounts of liquid oil that can be readily collected and pumped, the high-capacity flare burners offer the best approach. For burning large quantities of oil that is mixed with snow or with combustible debris, open-pit incinerators are best suited. The disposal of large amounts of noncombustible materials, such as oil-soaked sand, is best accomplished by using rotary kilns. Stoker-type incinerators are best suited for small volumes of oil and can burn combustible solids as well as combustible material off incombustible matter (for example, burn oil-soaked gravel to give clean gravel). The list of incinerator types to be considered is not complete, but rather includes examples of those devices showing the greatest potential for disposing of oil and various oil/debris mixtures.

Flare Burners

For burning large quantities of liquid oil while suppressing smoke, commercially available flare burners appear to be the most practical choice. Flare units have been used to burn up to 1980 m^3 (12,000 barrels) per day of unrefineable crude oil during offshore well tests. This test oil brought up by offshore drilling platforms (while checking the potential capacity of new wells) usually contains water, mud, drilling compounds, rocks, and other impurities that would foul processing equipment. Some burners are capable of disposing up to 50% water/oil mixtures.

The size and weight of flare burners vary with manufacturers. A typical burner weighs approximately 550 kg (1212 lb). Each burner, with all auxiliary equipment (pumps, generator, etc.), might be loaded onto one or two HC-130 transports. The U.S. Coast Guard is investigating the feasibility of making open-flame burners on pallets transportable by helicopter to remote areas, with a minimum amount of assembly in a harsh, cold environment.

Firing the largest designed burner releases a tremendous amount of heat, especially at full capacity with its flame 50 m (165 ft) long and 4.6 to 6.1 m (15 to 20 ft) in diameter. The burner's 879-MW (3×10^9 Btu/hr) firing rate is equivalent to the combined heat input of six medium-sized refineries or a 300-MW power plant (Peterson, 1975).

Surprisingly, despite the great volume of oil consumed, a flare burner can be smokeless, even at high firing rates. Three major factors combine to achieve the complete combustion necessary for eliminating smoke: good oil atomization, combusted air infiltrated over the length of the flame, and water spray to control fuel cracking in the rich part of the flame. High oil pressure is needed for good oil atomization, with an oil pump providing the atomized pressure. This type of atomizer usually requires pre-heating of the oil to a temperature that lowers the viscosity to 15 to 20 centistokes. This low viscosity requirement will almost certainly necessitate pre-heating the product in cold regions before atomization.

It appears that the flare burner could easily handle even a large oil spill of 7950 m^3 (50,000 barrels) over a period of four to five days (Peterson, 1975). For a spill in which oil is contaminated only with small bits of rock, sand, and debris, this type of burner would be all that is required. However, for spills involving significant amounts of larger solid materials, an additional incinerating device will be required.

Open-Pit Incinerators

Three types of open-pit incinerators are being considered for the disposal of oil, oiled snow and ice, and other combustible materials: non-air-transportable, air-transportable, and earthen pits. Non-air-transportable incinerators are found at municipal dumps and industrial plants. Good incineration characteristics result from high burning rates, long residence times, and high flame temperatures. Extensive tests have been made in which many solid and liquid wastes have been burned with good results.

An air-transportable open-pit incinerator has been recently developed by Environment Canada (Lombard, 1979), as shown in Fig. 28. The design of the open-pit incinerator is an open box with a forced air blower, for recirculation of combustion gases that eliminate smoke. The overall dimensions are approximately 3.6 m x 2.1 m x 2 m (11.8 ft x 6.9 ft x 6.6 ft). Transportation of this open-pit incinerator requires 14 helicopter lifts. Each section of the disassembled incinerator weighs approximately 410 kg (904 lb), with a total weight of 10 tons. At least three personnel are required to assemble the incinerator. The unit is capable of incinerating oil-soaked burnable material at a rate of one ton per hour (though it is not designed to dispose of oiled snow or sand). The incinerator can be loaded using front-end loaders or manual techniques. The cost of this unit is approximately $50,000. It would be particularly useful in permafrost areas, where it is not possible to burn debris in earthen pits. When placed on a platform, the incinerator will not cause deterioration of permafrost.

Another open-pit incinerator, made by Kenting Oilfield Services Ltd. in Edmonton, is the Kleen-Up incinerator, which has been designed for transportation to a remote oil spill. Units are presently being built having pit dimensions of 2.1 m x 2.7 m x 2.4 m (6.9 ft x 8.9 ft x 7.9 ft) and having a weight of 13,600 kg (30,000 lb). Test results indicated that a heavy crude, having the characteristics of Bunker C oil, could be burned with up to 40% water by volume without auxiliary fuel and without visible smoke (Peterson, 1975).

The third technique of open-pit burning involves burning of waste oil and oily debris in an open earthen pit (ditch or trench). Once this material is ignited, a blower is activated alongside the pit to provide an abundant source of air for the burning process. This technique is particularly advantageous because it substantially reduces the amount of air pollution and confines the burn to a relatively small area. In addition, the trench burner is highly portable and for this reason makes on-site disposal in remote areas highly practical. This trench technique can only be used where the ground is suitable (such as in sand, gravel, or earth). This technique would not be practical in permafrost because heat would be conducted into the ground for

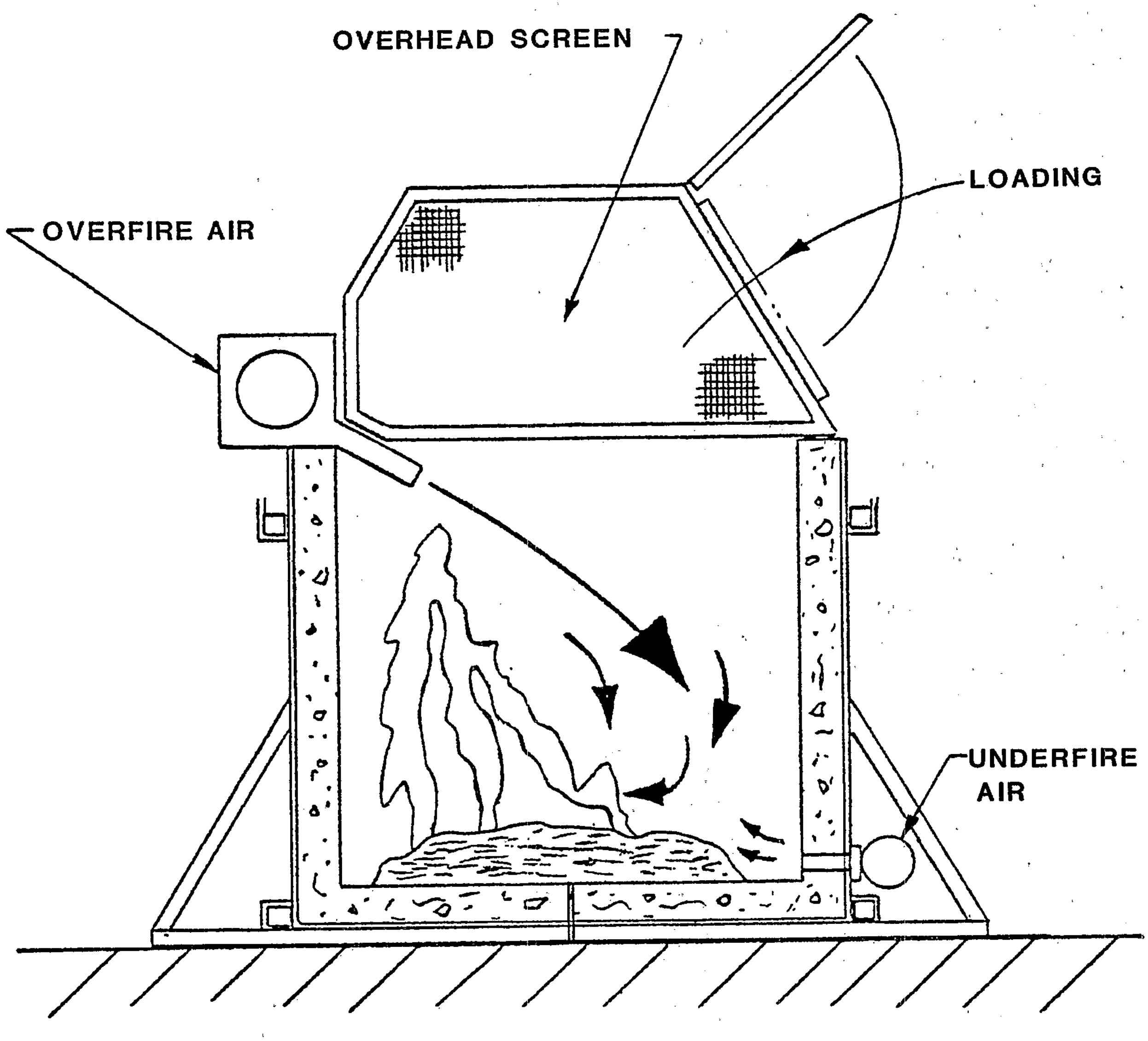


Figure 28. Air-transportable incinerator schematic (Lombard, 1979).

some distance on either side of the trench. In particular, burning on tundra vegetation can be hazardous, because once the insulating mat over permafrost is disrupted, erosion is inevitable. The time of year is critical. Summer burn vegetation is almost always destroyed and takes years to return. In winter, the effects are milder, and this method may be marginally suitable. Despite the fact that only a slight possibility of an explosion exists at an oil-spill site, certain precautions, nevertheless, should be taken, such as keeping all personnel 450 m (1500 ft) from the trench site.

Rotary Kilns

One type of incinerator that exhibits considerable promise for disposing of oil-soaked sediment and debris is the rotary kiln. The rotary kiln also provides the design flexibility for incineration of a wide variety of liquid and solid wastes. It provides a mixing action to achieve combustion of oil and oiled debris, which is especially desirable when disposing of oil-soaked sediments.

The problem of transporting a rotary kiln to a spill site is being studied under the auspices of the Petroleum Association for Conservation of the Canadian Environment (PACE). A small rotary kiln has been built and tested to burn contaminated sediments at a rate of about one ton per hour. Sediments can be as large as 2.5 cm (1 in.) in diameter. The basis of construction is materials normally available in the area. The incinerator is constructed from second-hand oil drums, angle iron, sheet metal, auto wheels, and lengths of wire rope. The driving power is provided by a vehicle with one wheel removed. The total cost for parts is a few hundred dollars. This kiln will burn out in a few weeks, but the fact that it can be locally built, when needed, out of scrap materials, outweighs the problem of a short life. A manual for construction design is available from PACE.

Stoker-Type Incinerators

Stoker-type incinerators are similar to coal furnaces. They consist basically of a grate on which burning takes place. They can be of the continuous feed or batch feed type. The burning is self-sustaining. They will burn combustible solids and will also burn combustibles off incombustible matter. One type of incinerator that can be home-made is often very practical for very small oil spills, up to 15.9 m^3 (100 barrels).

Home-made incinerators, such as 208-liter (55-gal) drums, would probably be sufficient for burning the oil and debris from small spills. A 208-liter (55-gal) drum incinerator can be constructed (Betts, 1973) by attaching a gas-fired bunsen burner to the inside surface of the drum firing into the wall or debris. Combustion air vents should be punched in the drum above the maximum oil level (approximately halfway up the drum). Alternatively, an inclined air inlet pipe of 2.5 to 5 cm (1 to 2 in.) in diameter could be positioned tangentially to the drum near the top (Figure 29). The resulting swirl of air around the inside surface of the drum would aid combustion and greatly reduce smoke. The air can be supplied by a small fan or compressor. The bottom of the drum can be left intact or removed and the drum set upright on a raised grating. In this case, the residue of the burned material falls

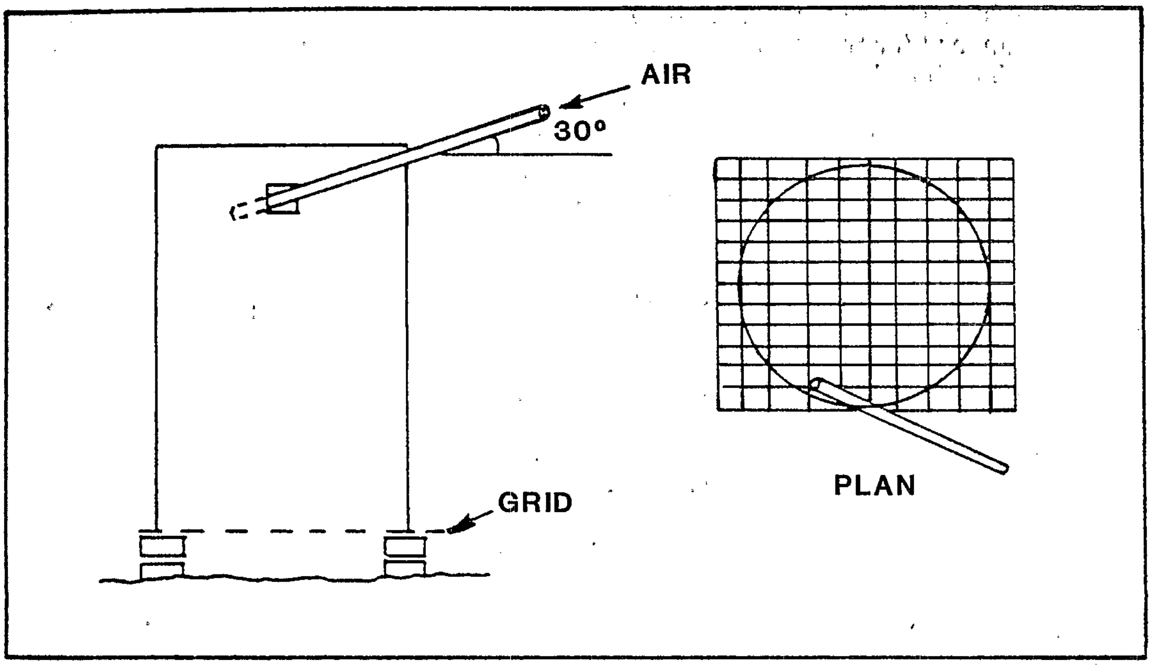


Figure 29. Simple drum incinerator (Betts, 1973).

through the grating and the incinerator can be operated continuously.

SALVAGE

Salvage may be considered a highly desirable disposal technique when local conditions permit this alternative. Salvage techniques include injection into the pipeline, injection into an oil well, refining the oil, and direct reclamation. The feasibility of these alternatives depends on the condition of the recovered oil, the logistics of the situation, and the availability of necessary equipment.

Pipeline Reinjection

One technique that is increasingly being utilized for disposal of oil discharged from a pipeline involves reinjecting that oil back into the pipeline. For example, discharged oil that has pooled along the pipeline may be reinjected at a nearby pump station, pipeline valve assembly, or directly at the spill site, with the on-scene installation of a T device that can be installed within a few hours. In some instances, techniques for heating the oil would have to be employed before reinjection to reduce its viscosity. Heating could be done by transferring the viscous oil into a warming tank before reinjection.

A second problem to be considered in terms of reinjection into a pipeline is that of separating the oil from any water that may have come in contact with it. A highly effective approach for dealing with this problem involves the use of an oil/water separator. Such a device can be made under field conditions by fabricating a metal box that has a bottom drain pipe and a valve, or by constructing a plastic-lined temporary holding pond. The water/oil mixture would be poured into the box or pond and allowed to settle, after which the valve is opened and the water decanted or pumped out. The remaining oil, assuming that it is free of debris, could then be reinjected directly into the pipeline.

If the discharged oil is contaminated by gravel or other debris, a mechanical separation technique must be employed. A portable screen can be used to separate the debris from the oil. The oil, in this instance, would be contained in a storage tank before being reinjected into the pipe.

Reinjection of recovered oil was recently used during cleanup operations for an Alyeska Pipeline spill (Buhite, 1979). Crude oil was collected in vacuum trucks and transferred to tank trucks, which were dispatched to the two nearest downstream pump stations for reintroduction into the pipeline. Initially, the crude was introduced into the ballast water treatment facility at Valdez Marine Terminal, but problems were encountered with debris. Thereafter, the oil was pumped first into a pit, then through screens to collect debris, next into the sludge pit sump of the ballast water treatment plant, and finally into the crude-oil storage tanks. All removed organics were incinerated. A 63-day cleanup effort resulted in 2465 m^3 (15,500 barrels) of crude oil being reinjected into the pipeline.

Direct Reuse

Oil directly recovered from spills could be put to a number of possible uses. Diesel and lubricating oil could be used directly as a low-grade heating fuel. The surface of unpaved roads is sometimes oiled to reduce traffic dust. Waste oils of many kinds are often used for this purpose, usually without processing. If the oil is not too viscous, it is simply sprayed onto the road.

LAND DISPOSAL

Land disposal is a viable technique for the disposal of spill debris. However, this technique should only be used after methods such as salvage and mechanical incineration have been fullyrejected. Disadvantages of using land disposal are groundwater pollution, the need for long-term monitoring, and high costs. Land disposal techniques include land cultivation, landfilling with refuse, and burial.

Land cultivation is recommended where debris size characteristics and access to suitable land permit. In land cultivation, the oil is degraded under aerobic conditions that result in relatively rapid breakdown of the bulk of the hydrocarbons. Landfilling with refuse is acceptable at individual burial sites or existing sanitary landfill sites. Landfilling is definitely less desirable than land cultivation because of the anaerobic conditions that greatly extend the period for groundwater pollution potential and monitoring. Burial is the least desirable method, with secondary pollution and slow anaerobic degradation creating problems. For any land disposal technique, the factors that should be considered are:

1. Permafrost,
2. Transportation,
3. Hydrology,
4. Topography, and
5. Geology.

The top insulative layer of permafrost soil may be damaged when disturbed by digging, vehicular movement, or sometimes simply by walking. In areas where disposal sites are made without regard to permafrost, solar heating may melt the ice in the soil around the site, forming a puddle that may begin to erode around the dump. Subsequent heating may melt deeper ice, thereby enlarging the pool. If the oiled material is to be buried, this erosion (thermokarst) process should be avoided. In addition to the possible problems of thermokarst action is the problem of providing a vegetative cover over the landfill site. In cold regions, it may be difficult to provide vegetation cover over the disturbed areas.

Hydrology and topography are also important factors to consider in establishing or identifying disposal waste sites. Those areas, unsuitable for the disposal of oil waste material from a topographic standpoint, are all low-lying areas where standing water exists. These low-lying areas include flatlands, adjacent to streams and rivers, areas covered by muskeg, and any other areas where either surface water or groundwater could become contaminated as a result of disposal procedures.

The geology of the disposal site should be investigated. Areas underlain by loose sand or gravel should not be considered for burial sites because of the high probability that oil seeping from the waste material could pollute that groundwater. Similarly, areas underlain by shallow permafrost are not suitable for disposal purposes because oil may penetrate to groundwater or permafrost and be carried to the surface when the groundwater eventually surfaces. Materials used to cover a burial site should have a sandy, silty consistency.

Information and guidelines required to assess the feasibility of using land disposal techniques in cold regions are as follows (Slusarchuk, 1978):

1. Locate site inland of maximum storm surge zone, or on land at least 3 m above mean water level.
2. Locate site as close as possible to spill area.
3. Check level of groundwater table and permafrost and their fluctuations. Investigate details of groundwater flows, such as direction, speed, and convection with other water bodies.

4. Do not locate sites on alluvial fans or active flood plains, particularly on braided rivers. This does not mean that high ground, which exists within alluvial fans as remnant landscape features that have not been eroded by the river, cannot be used.

5. Identify type of soil and its permeability to oil, particularly during the summer months. For summer construction, locate site and access roads on soil type with the following priority:

   a. Frozen sand, gravel, or rock deposits with little (less than 0.5 m) fine-grained soil at the surface,

   b. Frozen sand, gravel, or rock deposits with some (more than 0.5 m) fine-grained soil at the surface,

   c. Fine-grained soil with low ice content (less than 35% average), and

   d. Fine-grained soil with high ice content (more than 35% average) (though access roads can be located over this type of terrain in the summer, it is recommended that landfill disposal sites not be constructed in such terrain in the summer).

6. For winter construction (oiled debris has been stockpiled at a temporary storage site), locate sites on soil type with the following priority:

   a. Fine-grained soil with low ice content (less than 35% average),

   b. Fine-grained soil with high ice content (35-75% average),

   c. Frozen sand, gravel, or rock deposits with some (more than 0.5 m) fine-grained soil at the surface, and

   d. Frozen sand, gravel, or rock deposits with little (less than 0.5 m) fine-grained soil at the surface.

7. Locate sites on terrain that is as level as possible, and at least 50 m from the toe or crest of significant slopes greater than 10 degrees, and at least 100 m for significant slopes greater than 15 degrees. All ice-rich slopes must be checked individually to ensure that the above guideline is satisfactory for the actual field conditions at the site. Special attention will be required in all hummocky moraine terrain.

Depending on the specific field conditions and the potential danger to the environment of an uncleaned oiled beach, it should be understood that the guidelines may reasonably be altered in some cases. Oil-spill debris requiring disposal should contain mostly oiled soil, vegetation, rocks, sorbents, and other solids collected during spill cleanup. Any excessive oil should be recovered before or after debris collection but certainly before disposal. In many cases, debris consisting largely of soiled soil can be used as a road base, thus reducing or eliminating the need for disposal. For more information on disposal site location and techniques, refer to the reports by the Environmental Protection Agency (Stearns, et al, 1977) and Environment Canada (Slusarchuk, 1978).

Land Cultivation

The land cultivation process is known by various other terms, including land farming, land spreading, and land treatment. Regardless of the name, the process involves the spreading of oily wastes over the land so that subsequent cultivation and mixing will expose the oil to air and soil microbes (Stearns et al, 1977). This technique is deemed directly applicable to oil-spill debris that does not contain excessively large or bulky solids.

Oil-waste material can be applied from about 2 to 5 cm (0.8 to 2.0 in) thick in cooler, more humid northern parts of the United States and Canada. A tractor-drawn rototiller, plow, or harrow is used to break up the oily crust and mix it with soil organisms present in the surface layer. Practices vary from one location to another, with respect to the frequency of such mixing. A common practice is to plow the material to a depth of 15 to 20 cm (5.9 to 7.9 in) and to occasionally aerate and blend the oily waste with soil. In an EPA study (Stearns et al, 1977), all contacted practitioners of land cultivation till the soil/oil mixture at least twice a year for several years. In cold climates where microbial degradation occurs at a much lower rate, cultivation should be done more frequently.

Landfilling With Solid Wastes

Debris that is relatively free of liquid oil and water should not cause leaching problems in a conventional landfill, assuming the volume of debris is small compared with the waste volume in place. Thus, the option of sanitary landfill disposal of debris is usually available to all collected materials. Mixing with refuse will provide opportunities for oil and water present to be absorbed and, thus, impede outward migration. A properly situated and operated sanitary landfill can adequately protect underlying and surface waters from oil-spill debris contamination. No data has been obtained on the degradation rates of oil-spill debris on these landfill sites (Stearns et al, 1977). From numerous studies of sanitary landfills, it is known that all waste decomposition is anaerobic. Thus, oil is expected to be one of the last materials to decompose, if indeed it ever does. Estimates of the time for total decomposition range from 5 to 100 years (or longer), though the latter is the more realistic estimate in an anaerobic environment (Plice, 1948).

Burial

Burying, or landfilling oil-spill debris, is another commonly practiced disposal method, particularly when conventional sanitary landfills are relatively inaccessible to the oil-spill site or if landfill operators are unwilling or unable to accept the debris. Debris may be buried either below grade in excavated trenches or abandoned quarries or above grade over properly prepared subsoils, with appropriate barriers or berms placed around the disposal site perimeter.

In the past, sites with underlying impervious soils were selected as a fail-safe guarantee that oily materials would not leach from the disposal area. In the absence of naturally-occurring areas with such conditions, imported clay barriers have been placed to seal the disposal areas. Figure 30 shows a schematic cross-section of a debris burial site as designed and constructed by EPA (Jones, 1975).

The oiled debris should be layered with clean soil so that if oil is squeezed out of the debris there will be void spaces in the clean soil for the oil to occupy. The oiled debris should be placed in about 1-m (3.3-ft) layers with 0.3-m (1.0-ft) layers of clean material above it. In permafrost areas, it is important that the active layer does not penetrate down to the uppermost level of buried oil debris. If the soil contains ice, the terrain at the site should be built up and graded so that when thaw settlement occurs, water will not pond. Drainage ways should be provided around the area to ensure that the bermed area does not unduly affect the local drainage system. The berm then should be revegetated.

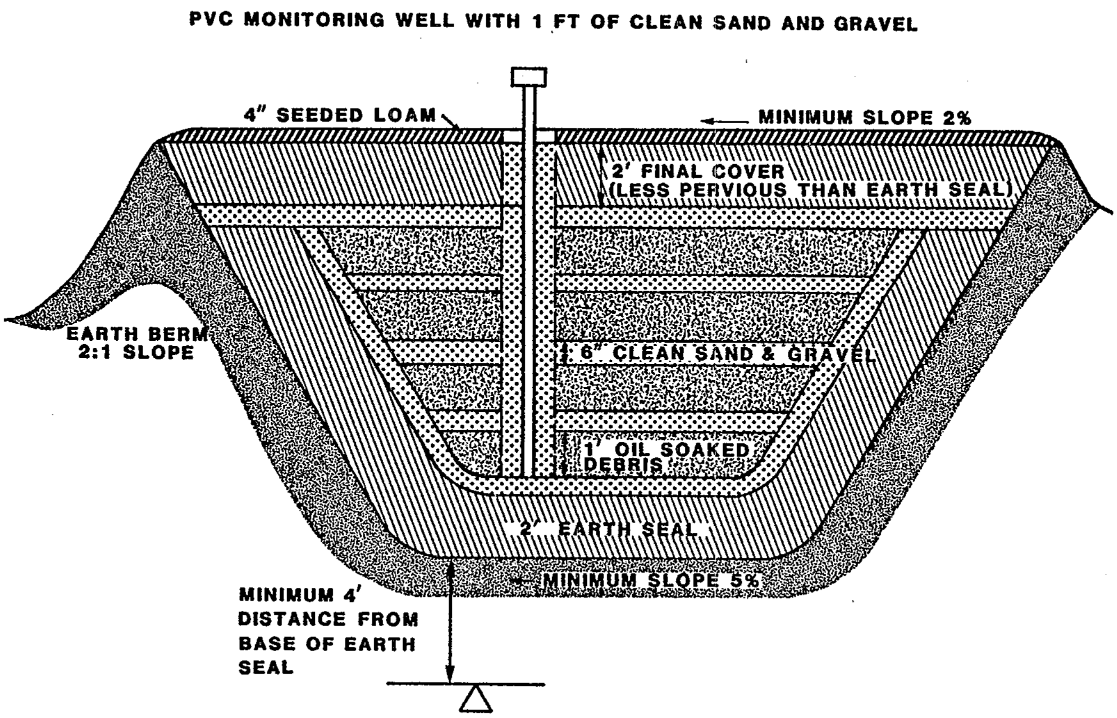


Figure 30. Schematic cross-section of debris burial site as designed and constructed (Jones, 1975).

A comparison of the advantages and disadvantages of land cultivation, landfilling with refuse, and burial is provided in Table 19. A second comparison of operating factors, environmental factors, and estimated costs for the three landfill techniques is listed in Table 20.

TABLE 19. ADVANTAGES AND DISADVANTAGES OF ALTERNATIVE DEBRIS DISPOSAL METHODS*

Disposal method	Advantages	Disadvantages
Land cultivation	o Oil is degraded, minimizing long-term environmental threat. o Land surface reusable for debris or other purposes. o Soil properties may be improved.	o Opportunity for oil volatilization; thus, increased air pollution. o Periodic plowing required; frequency depends on soil types. o Relatively costly. o Stockpiling at disposal site may be necessary. o Degradation may be slow in cold, wet climates. o May be impractical to implement during inclement weather. o Potential for plant uptake.
Landfilling with refuse	o Minimal equipment needs. o Relatively low initial cost. o Minimal site preparation. o Many landfills available.	o Land is dedicated to disposal indefinitely. o Influx of oil-spill debris may overtax available equipment and personnel. o Long - term pollution potential (e.g., leaching). o Long-term monitoring desirable.
Burial	o Oil encapsulated, minimizes volatilization. o Operations complete relatively quickly. o Land surface can be returned to pre-disposal appearances.	o Land is dedicated to disposal indefinitely. o Oil remains undegraded for long periods with consequent long-term pollution potential (e.g., leaching). o Long-term monitoring desirable.

* Stearns, et al., 1977.

TABLE 20. COMPARISON OF LAND DISPOSAL METHODS FOR OIL SPILL DEBRIS*

	Operating factors			
	Equipment needs	Flexibility	Environmental Factors	Estimated Costs
Land cultivation	Tractor, roto-tiller, disc, harrow, or plow	o Adaptable to many areas. o Requires no special skills. o Access road may be required.	o Minimal hazards if runoff controlled. o No danger to groundwater. o No spontaneous combustion problems. o Land may be tied up for disposal only temporarily (2-3 years).	\$4 to \$8 per yd^3 (not including cost to construct access roads, if any)
Landfilling with refuse	Use equipment available at landfill; generally a D-6 sized track dozer or larger	o For relatively small volumes of debris most landfills can readily accept. o Many landfills available. o Stockpiling usually unnecessary.	o Improper landfill location may cause undue threat of oil pollution. o Refuse can act as sorbent to impede flow of oil and contaminated water from site. o Possibility of spontaneous combustion. o Continuous long-term dedication of land to waste disposal.	\$0.80 to \$3.00 per yd^3
Burial	One D-8-sized tractor or larger. One backhoe may be necessary.	o Stockpiling may be necessary. o Access road may be required.	o Oil will remain undegraded at site for more than 100 years. o A plot of land, heretofore unused for waste disposal, will be dedicated for such long-term usage.	\$1.50 to \$5.00 per yd^3 (not including cost to construct access road, if any)

* Stearns et al., 1977.

SECTION 11

LOGISTICS

Oil-spill response logistics involve the on-scene movement of personnel, equipment, facilities, supplies, and the recovered product until the response effort is completed. They start with transporting the spill response team and its equipment to the spill area and include the needs of personnel at the spill site. The remoteness of likely spill sites, plus severe weather conditions (snow, ice, permafrost, and cold-region optical phenomenon) make spill response operations in cold regions more difficult than those in warmer climates. A discussion of spill response logistics begins with a review of air, aquatic, land, and amphibious transportation and the handling of equipment and is followed by a section on personnel requirements of food, shelter, clothing, and first aid.

TRANSPORTATION

Air Transportation

Air transportation is the prevalent method of emergency response used in cold regions, and it will undoubtedly continue as such in the near future. The combination of fixed-wing and rotary-wing aircraft during rapid spill response is generally constrained only by weather.

Several restrictions are imposed on flight operations in cold regions. Some of the problems include poor visibility, adverse weather, and darkness, as well as the difficulty of operating aircraft in extremely cold ambient temperatures. In addition, in remote areas such as in Alaska, problems include poor runway or landing strip conditions, limited availability of alternate air fields, limited availability of adequate air navigation systems, limited availability of fuel, and inadequate ground support. Many of the visibility problems common in cold regions were discussed in Section 5. Many advanced air bases are suitable only for visual flight rules (VFR), which means that in a whiteout, in blowing snow, or darkness at an inadequately lighted field, landings of fixed-wing aircraft could be interrupted. Helicopters are able to operate VFR under lower ceiling and visibility conditions than fixed-wing aircraft. However, helicopters are more vulnerable to icing conditions and do not have the endurance of fixed-wing aircraft.

Fixed-wing aircraft can be divided into three classifications of heavy, medium, and light transports, depending upon speed and payload capacity. Aircraft operating in the north have been summarized in Table 21 (Cather, 1978). According to this classification, disposal weight refers to the poundage

TABLE 21. AIRCRAFT CHARACTERISTICS: FIXED WING*

Name/Model	Fuel: 80/87	Fuel: 100/130	Fuel: 115/145	Fuel: JP1	Fuel: JP4	Fuel: JP5	Consumption, gal/hr (1 gal = 3.875 ℓ)	Undercarriage options: Wheels	Undercarriage options: Floats	Undercarriage options: Skis	Undercarriage options: Skids	Freight: Door size, in. (1 in = 2.54 cm)	Freight: Maximum package size, in. (1 in = 2.54 cm)	Freight: Disposable weight, lb (1 lb = .45 kg)
Heavy transport														
Boeing 727/QC				x	x		1,500	x				134 x 91	290 x 119 x 55	71,221
Boeing 737/200				x	x		725	x				134 x 86	154 x 55 x 83 106 x 86 x 80	56,000
Douglas DC6/AB		x	x				300	x				124 x 78	51 x 10 x 140 51 x 40 x 80	39,500
Lockheed Electra/L-188C				x	x		350	x				140 x 78	780 x 32 x 6 51 x 40 x 30	45,500
Lockheed Hercules/HC-130				x	x		680	x				120 x 108	552 x 114 x 103	81,435
Medium transport														
Bristol Freighter/170		x					200	x				92 x 76	90 x 75 x 360	16,200
DeHavilland Buffalo/DHC5				x	x		230	x				92 x 82	420 x 72 x 40	16,000
Douglas DC-3		x					80	x		x		84 x 70 Front 84 x 55 Rear	48 x 56 x 117 24 x 24 x 357	7,400 Wheels 6,400 Skis
Fairchild/F27 (Fokker)/F227				x	x		240	x				90 x 70	216 x 36 x 24	17,500
Hawker/HS-748 Siddley/MK 11A				x	x		210	x				48 x 54	336 x 6 x 6 60 x 48 x 42	17,536
Nihon/YS IIA				x	x		330	x				98 x 72	360 x 18 x 6 96 x 96 x 48	20,010
Light transport														
Beechcraft/G-18	x	x					38	x				60 x 38	96 x 18 x 24	3,900
Cessna/180, 185		x					12	x	x	x		38 x 39	78 x 20 x 30	1,400
Cessna/337G		x					17	x				40 x 37	38 x 35 x 18	1,570
Cessna/402, 421		x					36	x				36 x 42	28 x 34 x 34	2,250
DeHavilland Beaver/DHC-2	x	x					18	x	x	x		40 x 40	36 x 23 x 23 76 x 24 x 4	1,730
DeHavilland Otter/DHC-3	x	x					30	x	x	x		46 x 45	46 x 46 x 40 130 x 18 x 24	2,600
DeHavilland Twin Otter/DHC6-300				x	x	x	75	x	x	x		56 x 50	52 x 48 x 49 215 x 49 x 8	5,000
Short Skyvan/SC-7				x	x		75	x				78 x 78	74 x 78 x 80 223 x 72 x 60	5,000

(continued)

* Source: Cather, 1978.

TABLE 21 (concluded)

Name/Model	Runway requirements, ft (3281 ft = 1 km) Normal Paved	Gravel	Snow/ Ice	Water	Emergency Paved	Gravel	Snow/ Ice	Water
Heavy transport								
Boeing 727/QC	6,000	6,000	6,000		5,000	5,000	5,000	
Boeing 737/200	9,000	9,000			6,000	6,000		
Douglas DC6/AB	5,000	5,000	5,000		4,500	4,500	4,500	
Lockheed Electra/L-188C	5,000	5,000	5,000		3,600	3,600	3,600	
Lockheed Hercules/ HC-130	5,000	5,000	5,000		4,000	4,000	4,000	
Medium transport								
Bristol freighter/170	3,000	3,000	3,000		1,500	1,500	1,500	
DeHavilland Buffalo/ DHC 5	3,000	3,000	3,000		1,500	1,500	1,500	
Douglas DC-3	3,400	3,400	5,000		2,500	2,500	3,500	
Fairchild/F27 Fokker/F227	4,000	4,000			3,500	3,500		
Hawker/HS-748 Siddley/MK 11A	4,200	4,200	4,200		3,000	3,000	3,000	
Nihon/YS 11A	4,000	4,000	4,000		4,000	4,000	4,000	
Light transport								
Beechcraft/G-18	2,500	2,500	2,500		1,500	1,500	1,500	
Cessna/180, 185	1,500	1,500	2,000	3,000	1,500	1,500	2,000	3,000
Cessna/337G	3,500	3,500	3,500		1.800	2,000	2,000	
Cessna/402, 421	3,500	3,500	3,500		2,500	2,500	2,500	
DeHavilland Beaver/ DHC-2	1,500	1,500	2,000	3,000	900	900	1,500	2,500
DeHavilland Otter/DHC-3	1,500	1,500	2,500	3,000	800	800	1,500	2,500
DeHavilland Twin Otter/ DHC6-300	2,200	2,200	2,500	3,500	1,000	1,000	1,500	3,000
Short Skyvan/SC-7	2,200	2,200	2,200		1,500	1,500	1,500	

available to carry payload and fuel. The runway requirements are for fully-loaded aircraft. In actual operations, partial loads can be landed on shorter strips. The use of shorter strips is also facilitated by two factors that increase air density -- low temperatures and altitude -- and thus, the lift capability of the wings (Cather, 1978).

One of the most important fixed-wing aircraft for transporting spill-response equipment is the Hercules (HC) 130. The U.S. Air Force has a restriction from using the HC-130 aircraft from Barrow, Alaska, at temperatures below -20°F (U.S. Department of Transportation, 1968). Private industry has operated HC-130 aircraft in temperatures colder than -37°C (-20°F) during airlift operations to the North Slope of Alaska. The HC-130 has the capability of landing on 1-m (3.3-ft) thick ice with a runway length of approximately 1200 m.

Helicopters also can be defined as light, medium, and heavy, but this classification pertains only to load capacity (Table 22) (Cather, 1978). The relatively slow ferrying speeds eliminate helicopters as a long-range delivery vehicle. The major advantage of using helicopters is the small area required for landing and the flexibility, with respect to size and shape of packages that can be transported externally (Cather, 1978).

Aircraft usually available in the Arctic can carry equipment weighing up to 3629 kg (8000 lb), using prepared air strips, and can carry equipment weighing 1361 kg (3000 lb), using isolated, short-term air landing strips. Remote locations may also be serviced by helicopters, which can sling items of less than 3175 kg (7000 lb) a maximum distance of 483 km (300 miles) from base. There are some special helicopters available, such as the Sikorsky S63 Sky Crane helicopter, with a 10-ton lift capacity.

In Alaska, seasons determine when different types of aircraft can be used on different terrain. By November, aircraft converted to skis or wheel skis can be landed on frozen tundra or frozen lakes. Temporary air strips on land may be closed for extended periods, as a result of melting in the active permafrost zone or flooding. Aircraft could use wheels or skis on river deltas in winter, while floats would be needed along the coast in summertime. Helicopters are by far the most versatile transportation system available in spill-cleanup operations, and at least one helicopter should be available in remote area cleanup operations for emergency evacuation use. For large spills, particularly those in remote areas where few roads are available, it is best to establish helicopter landing pads and, if possible, a temporary landing strip for fixed-wing aircraft.

Aquatic Transportation

Ice conditions, water depth, and navigable routes generally determine the accessibility of marine vessels and spill-response equipment to an offshore spill site. In heavy ice conditions, ice breakers can prove to be an important response vessel. The arctic survey boats carried by Coast Guard ice breakers would provide excellent work boats for local transportation at, or near, the spill location. The main problem with using ice-breaker support is in the draft, typically greater than 7.9 m (26 ft), required by these large vessels.

TABLE 22. AIRCRAFT CHARACTERISTICS: HELICOPTERS*

Name/Model	Fuel 80/87	Fuel 100/130	Fuel 115/145	Fuel JP1	Fuel JP4	Fuel JP5	Consumption, gal/hr (1 gal = 3.875 ℓ)	Undercarriage options: Wheels	Floats	Skis	Skids	Freight: Door size, in. (1 in = 2.54 cm)	Maximum package size, in. (1 in = 2.54 cm)	Disposable weight, lb (1 lb = .45 kg)
Heavy transport														
Aerospatiale Puma/SA 330J				x	x		153	x				52 x 52		7,348
Boeing Vertol/ CH113				x	x		160	x				72 x 72	70 x 68 x 160	9,400
Sikorsky/S61L					x	x	140	x	x			47 x 64	64 x 38 x 72 360 x 6 x 6	8,150
Boeing Vertol Chinook/CH147				x	x	x	325	x	x	x		90 x 78	366 x 89 x 77	26,000
Medium transport														
Bell 205/204/A-1				x	x	x	75		x		x	90 x 49	90 x 90 x 48 132 x 24 x 24	3,512
Bell 212/CH-135				x	x		84		x		x	90 x 49	90 x 90 x 80 132 x 24 x 24	4,459
Sikorsky/S-58T				x	x		85	x				52 x 48	48 x 48 x 48	5,300
Sikorsky Sea King/CH-124					x		140	x	x			68 x 60	64 x 58 x 48 360 x 6 x 6	5,800
Light transport														
Aerospatiale Alouette II/ SA-318C				x	x	x	38		x		x	42 x 38	72 x 8 x 8	1,680
Aerospatiale Gazelle/SA-341G				x	x	x	40		x		x	57 x 40	48 x 48 x 36	1,574
Bell 47 Series/ G2, G3, G4	x	x					18		x		x	External racks		900
Bell 206 Jet Ranger/CH-136					x		25		x		x	35 x 36	45 x 36 x 34	1,259
Hughes/500-D				x	x		25		x		x	30 x 38		1,380
Sikorsky/S-55T				x	x	x	45	x	x			48 x 46	46 x 44 x 38	2,700

* Source: Cather, 1978.

In lighter ice conditions, tug and work boats could be used as support vessels. Fishing vessels could also be used for spill-response support in light ice conditions. The rigging and gear on some types of fishing vessels are particularly suited to oil-spill cleanup operations. The holding tanks on the fishing boats could be used also as temporary storage; however, secondary cleanup would be required. Barges could be used to support cleanup operations in areas of low ice concentration. The use of these barges as temporary storage would be extremely useful in cleanup operations of large oil spills. Tugs, work and fishing boats, and barges probably would be limited to local transportation and field operations at or near the scene of the spill.

Land Vehicles

Land vehicles must be capable of traversing a variety of terrains and surface features in cold regions, particularly in Alaska where access roads are few. Ice, water, snow, tundra, and permafrost are the most common terrains in Alaska's arctic regions. Subarctic Alaska includes all terrains described above, plus rocky or mountainous areas, glaciers, forest, and every imaginable type of beach, including mud. Problems in cold-region land transportation will be discussed, followed by a description of vehicle types most suited for these conditions.

Ice can be a most demanding terrain during oil-spill response. Leads and melt ponds impose a constraint, for that water must be crossed. Several types of land vehicles are either amphibious or adaptable to amphibious operations by the addition of flotation units. However, very few, if any, of the transport vehicles that have been operated under these conditions are capable of climbing out of the water over a 2-foot vertical edge (Eddington and Abel, 1971). Other problems include surface irregularities formed by the fracturing and deformation of ice. For example, the sail height on coastal pressure ridges can extend vertically up to 6 feet, halting most land transportation.

Traversing areas with deep, soft snow incapacitates most types of vehicles because of high centering. A suitable land vehicle does not exist for operation in all types of snow found in Alaska (Peterson et al., 1975a). One of the worst land surface conditions that can be encountered is a fresh layer of snow over wet, unfrozen tundra. Under these conditions, the vehicle will break through the snow cover, which has little or no bearing strength, and lose traction on the moisture-laden ground. The combination of snow, water, mud, and organic matter can quickly halt even the best machine (Harwood and Yong, 1972).

Permafrost poses unique problems to land transportation. Local environmental degradation may be particularly severe in permafrost terrain. There are two general regions of permafrost located in Alaska. The continuous permafrost zone is where essentially all land is underlain by frozen ground. The discontinuous permafrost zone includes those areas where permafrost is restricted to colder and/or more poorly drained sites, such as north-facing slopes and valley floors. Major problems arise when permafrost occurs on poorly drained, fine-grained sediments. These sediments contain large amounts of ice so that thawing makes the sediments unstable. Melting can result from the disturbance or removal of vegetation, or by warming temperatures (thermokarsting). Even a small physical disturbance, such as driving a vehicle across the tundra, can create thermokarst features. Some trails have remained cleared of vegetation for 20 years after a single traverse by a track vehicle. In some cases, these trails continue to erode (Richard and Slaughter, 1973).

The thermokarst problem has resulted in limitations being placed on off-road travel during some seasons in Alaska. The Alaskan Department of Environmental Conservation does not permit off-road travel from mid-May to mid-July. Rolligons may be used off road with a permit from mid-July to mid-September but are not permitted from mid-September until mid-November when the active permafrost layer once more becomes stable and hard (Batman, 1978). In the Rolligon the tires are replaced by a large balloon bag filled to 3 psi (20.7 kPa). This vehicle operates on the concept that the balloons, deflated to less than this amount, can assume the shape of an ellipse, allowing nominal ground pressure to be reduced and rolling resistance to be lowered. These vehicles have been successfully used in permafrost regions to carry heavy loads with very small ground disturbance.

To minimize the adverse effects of off-road vehicular trails on permafrost terrain, the following guidelines have been set up (Richard and Slaughter, 1973):

1. Take care in determining the route to be followed.

2. Avoid permafrost sites with high-ice-content soils.

3. Restrict traffic to low-ground-pressure vehicles (such as Rolligons).

4. Leave surface organic material intact.

5. Provide an insulating or wearing surface for the trail (such as logs).

Several types of land vehicles on wheels or tracks are suited for cold-region operations. The vehicles can be classified according to their running gear and include half-track vehicles, full-track vehicles, wheeled vehicles, and articulated vehicles. Table 23 summarizes land transportation vehicles commonly used in the arctic. A brief description of each of these vehicles follows.

Half-track vehicles have a running gear that combines the use of skis and tracks. An example of this type of vehicle is the light, load-carrying ski mobiles. These vehicles are propelled by a small floating track, mounted between the skis, that carries about 50% of the gross load. The success of these machines depends entirely on keeping them on top of the snow cover; so motion, resistance, and tractive requirements are kept to a minimum. The ground pressure required to operate these vehicles over snow is a prime restriction to their development into a true load-carrying machine (Peterson et al., 1975a).

TABLE 23. SUMMARY OF LAND TRANSPORTATION VEHICLES USED IN THE ARCTIC*

Vehicle/Manufacturer	Type	Nominal contact pressure (psi) (1 psi = 6.89 kPa) @NVW	@GVW	Approximate drawbar pull (lb) (1 lb = .45 kg)	Net Weight (lb)	Payload (lb)	Approximate personnel capacity
Caterpillar D-7	T	7.1	---	---	26,400	---	<4
Caterpillar D-8	T	8.5	---	---	40,600	---	<4
Weasel M-29C	T	---	1.8	3,000	4,800	1,200	<4
Bombardier HDW	T	1.26	2.2	---	8,000	6,000	---
Husky Eight	T	2.4	5.0	---	85,600	88,700	---
Foremost Yukon	T	1.4	3.0	---	17,800	20,600	---
Thiokol 1404	T	0.6	---	---	2,800	1,400	2
Volvo BV 202	T	1.2	---	---	6,406	2,000	---
Flextrack Nodwell FN 400	T	1.9	3.4	---	54,000	40,000	3
Flextrack Nodwell FN 600	T	2.1	3.6	---	83,000	60,000	3
Flextrack Nodwell FN 45TT	W	3.0	---	---	10,000	4,500	2
Flextrack Nodwell FN 100TT	W	2.0	2.7	---	14,000	5,000	2
Flextrack Nodwell FN 600TT	W	---	5.2	---	75,000	60,000	2
SkiDoo Snowmobile - 1 track	HT	0.2	0.6	---	251	400	2
SkiDoo Snowmobile - 2 track	HT	0.2	0.4	---	374	400	2
Rolligon RD-84 (Bechtel)	W	---	~4.0	---	26,000	20,000	---
Musk Ox/WNRE	T	3.0	---	---	50,000	40,000	<10
Amphibious Cargo Carrier T-116	T	1.9	2.2	---	5,350	3,000	13
Caterpillar D-2 (LGP)	T	3.5	---	---	14,000	---	<3
John Deere 420 Crawler	T	2.5	---	---	4,700	---	<3
Polecat MK II/WNRE	T	2.6	---	---	27,000	6,800	30
Bombardier Snowmobile	HT	1.2	---	---	5,000	2,500	12
M-7 Half-track	HT	---	1.0	---	2,600	500	2
Polecat/WNRE	AT	---	2.1	---	10,000	2,500	---
Kirsti Model KT-3	T	0.5	---	---	1.800	---	4
Kristi Model KT-4	T	---	---	---	2,800	2,000	8
WNRE Dinah	T	1.5	---	---	3,300	1,000	6
Otaco Ltd Sled - 10 ton	---	---	5.6	---	9,000	20,000	---
Otaco Ltd Sled - 20 ton	---	---	7.1	---	20,000	40,000	---
Cushman Trackster	T	0.5	1.0	1,000	1,040	800	4
Bombardier Muskeg Tractor	T	1.49	---	---	7,000	---	1
Bombardier Muskeg Carrier	T	1.69	---	---	8,000	8,000	2
Bombardier Muskeg Transporter	T	1.74	3.91	---	24,000	30,000	2
Bombardier Skidozer 301	T	0.62	---	---	6,000	---	2
Rolligon Model 6660	W	1.0	3.0	~5,000	10,500	12,000	<3
Rolligon Model 4450	W	1.0	1.5	~1,500	3,400	2,500	<3
Rolligon Model 8860	W	~1.0	~3.0	~7,000	15,500	~20,000	<4
Thiokol 1200 Series	T	0.7	1.0	---	6,550	1,900	10
Sno T'rrain/Consolidated	T	1.6	---	75,000	---	---	7
Tucker Sno-Cat 1500	T	0.84	---	---	5,800	1,650	6-8
Tucker Sno-Cat 1600	T	0.68	---	---	6,000	1,800	6-8
Tucker Sno-Cat 2700	T	0.55	---	---	7,800	7,300	6-8

Abbreviations: GVW - Gross vehicle weight; NVW - Net vehicle weight; T - Tracked; HT - Half-tracked; W - Wheeled; AT - Articulated tracked

* Source: Peterson et al., 1975a.

Full-track vehicles are the most successful class of self-propelled vehicles. While these vehicles may not have high mobility in snow, nonetheless, for economic reasons they appear to be better general-purpose vehicles than most other types. These full-track vehicles have superior drawbar performance. This is mainly due to the markedly reduced motion (rolling resistance). There is a higher performance in snow or muskeg when using the full-track vehicle with a Space Track, in comparison with conventional tracks. Space Track is a track with large spaces between the grousers and links. The indications are that the improvements with using this running gear can only be achieved in small machines (below 10,000 lb [4540 kg] gross) (Peterson et al., 1975a). Wheeled vehicle use in cold regions is limited to cleared ice, snow, and other prepared roads. Specialized, wheeled vehicles with large-diameter, low-pressure tires, such as Rolligons, have been tried with some degree of success in unprepared ground.

Articulated vehicles are designed in such a way that all four tracks are in contact with the soil and all tracks run at the same speed (or slip). The front and rear part of the vehicle must be independently free to move (roll, pitch, and steer). An articulated vehicle can be thought of as two vehicles back to back, coupled by a universal joint and driven by one motor through an articulated shaft. Articulated vehicles have disadvantages, the main ones being the splitting of the vehicle and the complication in driving. However, units do exist that offset these disadvantages.

Sleds can be very useful in cold regions. The sleds that have the most highly developed suspension and frames are the Canadian Northland Sleds. They have spring-mounted runners made of aluminum. These sleds were developed for two-ton and four-ton loads.

Amphibious Vehicles

Air-cushioned vehicles (ACV) ranked second only to helicopters in ability to traverse cold-region terrain over short to intermediate ranges (Peterson et al., 1975a). ACVs have great potential for arctic transportation. An advantage of ACVs over aircraft is the capability to operate in conditions of low visibility, such as fog or low clouds. The ACV craft have many advantages over conventional vehicles, primarily speed, amphibious nature, low freeboard, freight capacity, stability, and the ability to travel over tundra, marsh, rotting coastal ice, or ice floes.

The Canadian Arctic Marine Oil Spill Program (AMOP) (Meikle, 1978) has developed the use of ACVs as platforms for oil-spill cleanup in ice-infested waters. From field trials conducted by the Canadian Coast Guard it was concluded that the air cushion does not disturb an oil slick and that the craft could be used for recovery operations. Practical oil spill countermeasure exercises were conducted using an ACV as a transport and work platform.

The many advantages of the ACV used in the arctic must be weighed against a number of potential problems. ACVs may develop performance loss and maintenance problems from constant operation over rough, broken ice. The current high cost of such vehicles ($2.5 million for the Bell Voyager) (Peterson et al., 1975a) may partially limit its use as a spill-response vehicle. In spite of possible problems, the ACV is well suited for traveling over the tundra and marsh year-round, with few adverse environmental problems, and it can transport equipment and men to aquatic areas that would be inaccessible to other vessels.

Preparation of Equipment for Transport

Personnel are generally transported to the scene of an oil spill much more readily than heavy equipment. Therefore, the necessary equipment should be ready to be deployed once it arrives on-scene. Large transportation vehicles will be at a premium or nonexistent in remote areas, particularly in Alaska. Equipment must be pre-packed in the smallest practical containers that are adaptable to all potential conveyance methods of handling. Methods of handling equipment would include (Peterson et al., 1975a):

1. Hoisting by crane or helicopter, using slings,

2. Raising or lowering by forklift,

3. Dragging on sleds or skids, or

4. Manhandling.

All equipment requiring protection from the environment or from shock or vibration must be pre-packed in shipping containers that afford the necessary protection, regardless of the mode of transportation. The shipping containers must further be safely handleable by all means of handling tabulated above, whenever possible. Proper identification and ready access for maintenance and/or inspection are also mandatory. For remote areas, the largest container size desirable is one that will slip readily into the bed of a pickup truck, 1.2 x 1.8 x 2.4 m (3.9 x 5.9 x 7.8 ft). The maximum desirable weight to permit manhandling is less than 91 kg (200 lb). Equipment pre-packaged in small containers should be stored in larger cargo containers for primary transportation.

Some oil-spill cleanup and containment equipment, and some forms of field support equipment, will exceed the limits of size and weight for manhandling. This larger equipment must be suitably pre-packed for handling by any of the other methods tabulated above. As a general rule for transportation within Alaska, the larger equipment should be broken down to the smallest, practical size, even at the expense of additional assembly time in the field. Too many instances are likely where a large, heavy package might never reach its destination, especially in the arctic. (This is in contrast with procedures in the more heavily populated areas of the lower 48 States, where mobile high-capacity cranes and similar gear are usually available.) In no case should a single package exceed the size or weight that can be unloaded from an HC-130 aircraft at a remote airfield -- approximately 2.4 x 1.5 x 6.1 m (7.8 x 4.9 x 20.0 ft) and 6800 kg (15,000 lb).

ESTIMATION OF CLEANUP CREW AND EQUIPMENT NEEDS

Considerations involved in estimating cleanup crew and equipment needs for an oil spill in cold regions include the following:

1. Is there ice present? In what form? Land, sea, or freshwater ice? Is there snow present?

2. What kind of oil has been spilled? How is it behaving? (Thick, not fluid; or light oil, moving over ground, ice, or water.)

3. What are the environmental conditions surrounding the spill? How are those conditions affecting the movement of the oil? How will those conditions affect the movement of equipment and personnel?

4. What kind of decisions has the OSC made about the type of cleanup needed for the spill? Can the area stand the use of heavy equipment such as bulldozers and trucks, or cranes, or mobile incinerators? Is it an area that requires the use of hand tools exclusively, or almost exclusively? Is it an area where there is a great amount of cleanup required, or can much of the area be left to weather naturally?

5. How accessible is the area, to what types of personnel movers? How far away is the stockpiled equipment? How can it be moved, and in what time frame?

6. How well trained are the personnel that are being used to clean up the spill? (In most cases, better training means fewer people need to be used in any given situation.)

7. Assuming a winter spill, what kind of cold-weather gear is available for the cleanup personnel? In general, the colder the weather, the more personnel will be required because of the rapid decrease in efficiency after having been in the cold. What kind of rotation schedules do you need to use for these personnel?

8. What kind of mechanized equipment is available that will work in cold conditions? How far away is that equipment?

9. How many people are available in the area? What can you afford in terms of cost to get them there if they are not already there? How cost-effective would it be to bring in other people, or can the job be done over a longer period of time with fewer people?

For example, personnel and equipment needs are estimated for a cold-region oil spill of 7950 m^3 (50,000 barrels) in Table 24 with the following scenario: A subsea oil blowout occurs in winter in the Beaufort Sea, causing 7950 m^3 (50,000 barrels) of oil to be lost. In responding to this incident, the on-scene coordinator would have to consider recovery of the oil in three environments: on the beach, on open water, and on and under ice. For each environment a different mix of personnel and equipment would be needed. Requirements for support personnel are difficult to estimate. In any case, the following specialties should be represented at the scene: medical, communications, heavy equipment repair, plumbing and heating, food preparation and service, and possibly clothing issue.

TABLE 24. ESTIMATED CREW AND EQUIPMENT NEEDS FOR A 7950-m^3 (50,000-BARREL) OIL SPILL UNDER WINTER ICE COVER

Activity	Equipment	Nonsupervisory personnel
Surveillance	2 helicopters 1 small boat	4 pilots 1 boat operator
Containment	1 crane 6 bulldozers 3 front-end loaders 2 ditch witches 4 iced augers x marker buoys x boom lights x anchors	24 heavy equipment operators - two for each piece of equipment 28 workmen
Recovery on and under ice	2 current meters 2 tank trucks 2 mop skimmers 4 pumps sorbents igniters/promoters generators/lights tracked vehicles surface barriers with lights storage bladders/drums	1 current meter technician 4 drivers 4 operators 4 workmen 10 general laborers
Recovery on open water	6 small boats 1524 m (5000 ft) of 12 x 24 boom 610 m (2000 ft) of small harbor boom Heavy-duty skimmer 1 small storage/disposable barge of 954 m^3 (6000 barrel) 2 tugboats portable skimmers pumps and bladders	12 boat operators 2 skimmer operators 20 workmen 8 tug crew
Recovery on the beach	2 helicopters 6 all-terrain vehicles 6 small workboats portable skimmers sorbents weed burners pumps and hoses shovels and rakes, etc.	4 pilots 12 operators 6 boat operators 200 general laborers
Disposal	1 barge-mounted incinerator 3 portable incinerators 20 weed burners 200 air-deployable igniters	10 incinerator operators
Support	onsite and offsite ca-pers command center communications center portable and mobile communications equipment	

REQUIREMENTS FOR PERSONNEL

Training

Oil-spill personnel must be psychologically and physically prepared to work safely and effectively in cold environments that present special problems for oil-spill response efforts. Tasks that might be simple under normal conditions would be arduous and time-consuming in the face of extreme wind and cold; incidents that are of minor importance in warmer climates might quickly develop into life-and-death situations in the arctic or other cold regions. Survival is not a matter of luck. Personnel training is an essential part of oil-spill response operations in the arctic.

The following material on training describes the principal hazards that may be encountered in cold regions and discusses topics that should be covered in cold-region training sessions. Training sessions should be geared to persons with no experience in cold-region operations.

Physiological Problems--
Cold regions present special problems to personnel operations. The main hazards are briefly defined below:

Frostbite--Freezing of tissue can occur whenever the temperature is below 32°F (0°C). The danger of frostbite is greatly increased in conditions of high wind and sub-zero temperatures.

Hypothermia--Lowering of body temperature is caused by insufficient generation of body heat. Hypothermia may occur above and below freezing and is especially common in wet conditions. The lowering of body temperature may result in death if the condition is not recognized and treated.

Wind Chill--Wind chill refers to the combined cooling effect of wind and cold. Windy conditions may contribute greatly to frostbite and hypothermia.

Dehydration--Dehydration of body fluids occurs rapidly in cold environments because of low humidity, wind, intense sunlight, diminished thirst, and diminished water intake. Dehydration increases fatigue, impairs mental activity, and lowers tolerance to cold (National Science Foundation, 1974). This condition contributes greatly to hypothermia and frostbite.

Snowblindness--Burning of the retina of the eye results from ultraviolet rays of the sun. Ultraviolet radiation is particularly intense in cold regions because of the highly reflective properties of ice, snow, and water.

Sunburn--Like snowblindness, sunburn results from exposure to ultraviolet rays of the sun. Sunburn is a common problem in cold regions.

Carbon Monoxide Poisoning--Carbon monoxide poisoning can occur whenever there is an engine running or a stove burning in an insufficiently ventilated space. Carbon monoxide is absorbed by the blood more readily than oxygen, and the oxygen supply to the body may be effectively choked off by high levels of carbon monoxide.

From a training standpoint, the main considerations are prevention and treatment of these hazards. A basic understanding of these problems will minimize the potential danger and discomfort of cold-region activities.

Clothing--

The selection and proper utilization of clothing is a main concern for cold-region personnel. The main clothing considerations are protection from cold, wind, and wetness:

1. Minimize perspiration.
2. Keep insulation dry.
3. Use insulation that retains its insulating ability when wet.
4. Wear layers of clothing to permit adjusting to varying conditions.
5. Wear windproof clothing for protection against wind.
6. Wear loose clothing to prevent restriction of blood circulation.
7. Clothing should be durable.
8. Fasteners should be operable with mittens.
9. Avoid contamination of clothing by petroleum liquids.
10. Wear coveralls that can be discarded when working directly with oil.

Emergency Procedures--

Cold-region oil-spill response personnel must be prepared for emergency situations that may involve basic survival in adverse weather conditions. Emergency situations are most likely to occur while traveling to and from oil-spill locations. However, injuries or accidents may occur at any time during an oil-spill operation, and relatively minor incidents may become quite serious in remote areas or in adverse weather conditions. Rescue may not be immediately available. Emergency survival training is important for all personnel working in cold regions. This training should include in-depth study of:

1. Psychological considerations,
2. Initial emergency procedures such as vacating a hazard area, administering first aid, collecting survival gear, attempting radio contact, etc.,
3. The decision to stay with vehicle or aircraft ,
4. Methods of building emergency shelters (snow caves and trenches),
5. Principles of first aid,
6. Principles of the use of fire and fuel,

7. Rescue signalling, and

8. Methods for obtaining water.

Guides to Cold-Weather Operation

The following list of hints (do's and dont's) will aid those who are working in cold regions. These are hints on safety and accident prevention (partly from National Science Foundation, 1974).

1. Always -- whether in camp, in a vehicle, on foot, or in the air -- have a plan in case of an accident.

2. Dress for the occasion; do not overdress, for this can be just as hazardous as underdressing.

3. Use the buddy system during all operations. Keep an eye on each other -- watch for moving machinery, frostbite, etc.

4. Use your head. Take time to think, plan, and organize. Analyze the weather, the terrain, the available energy, and resources for a given operation.

5. Do not fight the environment. Conserve energy. Go around obstacles, not over or through them.

6. Never touch cold metal with your bare hands. They may stick to the metal and you may lose skin while getting free. Wear thin contact gloves that allow dexterity while providing some protection.

7. Be careful in handling fuels. Contact at cold temperatures can induce immediate frostbite.

8. Do not smoke during fueling operations. Do not smoke in airplanes without the pilot's permission. Never smoke if you smell gasoline.

9. Check all equipment before fueling to make sure you are using the correct fuel.

10. Make sure your quarters and equipment are well ventilated. Never sit in an idling vehicle (to utilize heater). Carbon monoxide poisoning is a real danger.

11. When temperature permits, remove bulky outer clothing before operating equipment with exposed moving parts.

12. Never attempt to operate an unfamiliar piece of equipment. Admit that you are inexperienced and seek help.

13. Do not overload electrical circuits. Obtain permission before plugging in heating elements or increasing demands beyond a normal work load.

14. Stay away from edges of ice, whether it be bay ice, shelf ice, ice foot, or glaciers. Keep away from the top and bottom of ice cliffs.

15. In the event of a sudden blizzard or whiteout while away from camp, dig in for shelter. Wandering aimlessly is an almost sure way of getting lost.

16. Wear leather gloves at all times while flying. They are indispensible protection in case of fire in a ditching or crash situation.

17. Do not overeat. Eat small amounts often to keep blood sugar and strength up. Maintain an eating regime that provides a balanced diet and provides adequate bulk.

18. Drink plenty of water to keep body fluids at a proper level.

19. Learn basic first aid. Medical personnel are rarely present at field accidents.

Field Support Requirements

Field personnel must be provided with adequate food, clothing, and shelter for the duration of oil-spill operations. Provisioning must be complete, and all necessary equipment (beyond personal items) must be available within short notice. Difficulties often may be encountered in providing appropriate equipment and supplies to sustain operations in many parts of Alaska, and the development of support plans and requirements is imperative. Cost, availability, and/or personal preference may dictate the selection of field support equipment.

Since polar regions are characterized by a wide range of climatic extremes, support requirements will vary with season and environment. Winters in the arctic and in the Alaskan interior tend to be very dry and cold, whereas winters along the Alaskan coast and in subarctic regions tend to be wet and cold. Alaskan summers are typically cool and wet. Equipment should be provided that is appropriate for the conditions of a given area and season. (Mosquito headnets are not useful in winter, nor are down mittens in summer!) Methods must be developed for issuing the appropriate provisions and supplies. Personnel should be prepared for the worst possible expected conditions but should not be overburdened with useless or excessive items.

Maintaining morale is a primary objective in the consideration of field support requirements. This is partly accomplished by providing a well-organized support plan and ample supplies of food, water, clothing, shelter, and sanitary facilities. Living and work conditions should be made as comfortable as possible, so that field personnel expend a minimum of energy on basic survival functions. Up to 3 days may be required for the initiation of full support systems, depending on the conditions and location of an oil spill (Peterson et al., 1975a). Thus, initial response teams should be equipped to sustain themselves fully for a number of days.

Safety of response personnel is paramount, and operations should be suspended or delayed if conditions present unnecessary risk to life or limb. A certain amount of danger is inherent in all oil-spill operations, especially in cold regions, and these dangers (air travel, mechanical operations, cold, storm, etc.) should be recognized. Potential dangers can be minimized by the selection of qualified personnel who are knowledgeable and capable of carrying out cold-region duties. Operations in conditions of extreme wind, wet, and cold should only be attempted by individuals experienced in cold-weather survival. Contingency plans should be developed for handling emergency situations. Whenever necessary, personnel should be advised of basic cold-weather operating and survival procedures presented earlier in this subsection.

Food Requirements--

Strenuous activities, especially in cold conditions, require a high calorie intake and increased amounts of protein, fat, and vitamins in the daily diet. Carbohydrates should be included for daytime consumption for quick energy. Foods that are more substantial in protein and fat will yield large amounts of calories from 12 to 14 hours after ingestion. The cold-weather diet recommended in the Navy Polar Manual is compared below to an average temperature diet in Table 25 (Peterson et al., 1975a):

TABLE 25. COMPARISON OF DIETS FOR TEMPERATE AND COLD REGIONS

Food element	Temperate regions	Cold regions
Carbohydrates (4.1 cal/gm)	53%	40%
Fats (9.3 cal/gm)	35%	40%
Protein (4.1 cal/gm)	12%	20%
First-class proteins (meat, milk, and eggs)	(5%)	(10%)
Total calories	3500	5500

Hot, nourishing meals will do much for morale and are desirable for extended periods. Frozen, precooked and prepackaged meals are recommended because they are easy to handle and yet offer wide meal selection. These meals can be heated in a portable oven and can be thawed and refrozen several times without spoilage. Field lunches in cold regions should consist of high-energy foods, such as pemmican, raisins, candy, biscuits, etc. Military C-rations are suitable for initial response efforts. Daily meal requirements should be prepackaged so that they are available for immediate dispersal to site locations in the event of an oil spill.

Water is almost never a problem in the arctic, as ice, snow, and streams are readily available in most areas. Surface water should always be treated by boiling (for 20 minutes) or by chlorination, until it has been tested and found safe. The daily intake of liquid should be between 2 and 4 quarts per person per day, and an additional 2 to 5 gallons per person per day should be available for cooking, washing, and so forth (Peterson et al., 1975a).

Clothing Requirements--

Hands and feet are particular problem areas. Mittens should be layered -- an outer protective shell, inner mitts for warmth, and gloves for dexterity. The half-inched, felt-lined, leather and rubber-soled boots (Sorrel type) have proven to be very versatile in Alaska, as the tops afford some ventilation and the bottoms give protection from wetness. In extremely wet and/or cold conditions, the Army Mickey Mouse or bunny boot has proven to be very satisfactory because the insulation is completely encased in rubber, thereby keeping the insulation dry. These boots tend to be bulky and clumsy, but warm. Mickey Mouse boots should be worn only with thin socks that absorb perspiration.

Windproof, waterproof garments should be provided. Usually, a garmet impervious to rain is also impervious to body moisture, and condensation will often occur within the garment. A few materials and designs have reduced this problem (for example, Goretex, foam-backed nylons), but they are generally expensive and less versatile. Many waterproof garments are designed with ventilation flaps (usually on the back or underarm). These are not recommended for arctic conditions because of high winds and driving rain that will penetrate the openings. Zippered rain parkas may be desirable because they are easy to ventilate. Wind garments should be breathable (that is, they should allow for the escape of body moisture). Wind parkas will offer sufficient protection against snow in cold weather. Large pockets are desirable in outer clothing.

Special consideration should be given to oil protective clothing. Oil will permanently affect most clothing materials, rendering them unpleasant and less effective. Expendable coveralls and gloves should be used when working directly with oil. This clothing should be provided in addition to wind and rain gear.

Insulating materials should be chosen according to the particular climate. Cotton and down clothing should never be used in wet conditions since they lose most of their insulating capacities when wet. Wool has proven to be an excellent insulating material in wet weather. Synthetic fiber and pile materials also work well. Pile is noted for its light weight and resistance to water; in addition, it dries very quickly (even by body heat) when excess water is removed by wringing.

Oil-spill operations frequently involve heavy work, and garments should be durable and tough to resist wear and tear. Plastic zippers are usually more reliable than metal zippers. Quality materials and workmanship are imperative. Special items of clothing may be required, depending on conditions and the nature of the spill operation.

A recommended list of clothing is presented in Table 26. The equipment listed is issued to personnel of the Pacific Strike Team. Always equip personnel for the worst possible conditions. Supply too much rather than too little clothing. The selection of specific clothing items should be delegated to a person experienced in cold-weather operations.

TABLE 26. CLOTHING ISSUE (PACIFIC STRIKE TEAM)

Item of clothing	No. of units
Protective:	
Foul weather suit, waterproof	1
Foul weather suit, windproof	1
Insulated jacket, with hood	1
Wool hat	2
Balaclava and/or facemask	1
Wool mittens	2 pr.
Leather or nylon outer mitts	1 pr.
Wool gloves	2 pr.
Leather outer gloves	1 pr.
Sorrel-type or other appropriate boot	1 pr.
Boot liners for above	2 pr.
Insulating:	
Medium-weight sweater	1
Wool shirts	2
Wool underwear, bottom and top	2
Wool trousers	2
Wool socks	6 pr.
Other:	
Helmet, with liner	1
Coveralls	3 pr.
Work gloves	3 pr.
Duffel bag	1

Shelter Requirements--

Adequate shelters are a necessity in cold regions, and durable structures must be available for extended operations. In some areas it may be possible to house all or part of a response team in existing facilities. Potential existing sources of shelter include Coast Guard cutters or other large vessels, and existing government or private facilities, at or near the spill location. Frequently, oil operations in Alaska are located in remote regions, and temporary portable shelters must be available. The following requirements are desirable in the selection of portable, temporary shelters:

1. The shelters must be transportable by aircraft, ship, or land vehicle. The restrictions on weight and size are imposed by the suitability of transport in conventional aircraft.

   Dimensions have been defined according to HC-130 aircraft, which can take containers up to 3 m (10 ft) long, 2.4 m (8 ft) wide, and 2.4 to 2.7 m (8 to 9 ft) high. Air-drop capability is highly desirable for the added ease and speed of transport.

2. Shelters must be adaptable to the constrictions of the environment. Thus, they should be able to withstand high winds. Shelter components must be effective in muddy, rocky, or variable terrain.

3. Shelters must afford adequate protection from wind and cold. Shelter design and materials should minimize heat loss in very cold temperatures. Shelters must be insulated and provided with heating units.

4. Shelters should be easily and rapidly erectable to avoid diverting personnel energy from cleanup efforts.

5. Shelters should be durable and reusable.

6. Shelters must be completely self-contained, including all the required power, heating, and cooking facilities.

See Peterson et al. (1975a) and U.S. Army (1972) for a thorough investigation of available shelters and shelter materials.

Miscellaneous Requirements

Survival and Emergency Equipment--

Whiteout or storm conditions may occur very rapidly in cold regions, and personnel should stay put until conditions improve. The following basic survival items should be carried at all times by each individual:

1. Knife,
2. Signal mirror,
3. Compass,
4. Whistle,
5. Flashlight,
6. Distress flares (light or smoke signals),
7. Sunglasses and suncream,
8. Emergency blanket (space blanket), and
9. Food.

These items can be carried in pockets or in a small pack.

In addition to personal items, a more extensive emergency kit should be available to response teams. THis kit should contain medical supplies and sufficient equipment for survival in disaster situations. Emergency items include:

1. First aid kit (including foot powder, suncream, lip ointment, etc.),
2. Emergency food and stove,
3. Tarps and/or tent,
4. Snowsaw and shovel,
5. Axe or hatchet,
6. Blankets and/or sleeping bags,
7. Firearm,
8. Signal equipment (mirrors, flares, etc.).

Personal Equipment--

Personnel should be advised of the personal equipment required for a given operation. Sufficient quantities of underclothing (socks, underwear, trousers, shirts, etc.) must be provided to personnel. This clothing should be wool whenever possible. Eating utensils and sleeping gear may or may not be supplied to field personnel, and this should be indicated (and should be supplied along with the shelters). Toiletries must be provided by the personnel.

Communications Equipment--

Successful operations depend on effective communications, and portable radios should be employed for coordinating personnel activity and movement. Communication is vital to safety, especially in darkness or storm. Cold-weather performance is important in the selection of two-way radios. Problems may occur if cold objects are taken into a warm shelter, thereby causing condensation that may freeze upon return to the cold.

Fuel Requirements--

Fuel is necessary for cooking and heating and for the operation of vehicles and equipment. Ideally, various equipment should utilize the same fuel to minimize the variety of fuels required. Fuel should be stored away from living quarters, and provisions should be made for safe transport.

Sewage Disposal--

Sewage disposal may be a serious problem, because of inadequate drainage in permafrost and because of the possibility of malfunction of chemical toilets in cold weather. Sewage disposal should be confined to a specific area.

SECTION 12

RESTORATION

The definition of a cold region, as presented in this manual, encompasses a tremendous amount of variation in biotic communities; because of this variation, it would be impossible to present restoration techniques for all of these environments. Hence, in this chapter, two major cold-region biotic communities are dealt with: the arctic, including the tundra vegetation formations; and the subarctic, including taiga and northern boreal forest formations. There are two major reasons for dealing with the arctic and subarctic in this restoration section: (1) they are the most sensitive to spilled oils; and (2) they present the most restoration problems. Restoration is easier in southern areas where growing seasons are longer and climatic conditions less severe, though many of the same principles presented here apply to northern areas as well. In agricultural areas, restoration is generally a matter of frequent additions of fertilizers and tillage (Powell and McGill, 1978).

Arctic and subarctic plant communities vary from low-elevation coastal communities to high-elevation alpine plant communities; however, the sophistication of restoration techniques for these cold regions does now allow treatment of each of these various plant communities. For example, in dealing with a coastal spill in the subarctic, the only available literature concerning restoration is the general precautions presented by Maiera et al. (1978) and the general species information as presented in this review.

NATURAL RESTORATION IN COLD REGIONS

In studying plant succession in areas where oil spills have occurred, some researchers have found that many plant communities will naturally regenerate. Johnson and Van Cleve (1976) have found that *Carex aquatilis* and various willows and birches are tolerant to spilled oil if the oil does not penetrate the soil surface and kill the root systems. In many cases, regrowth of these species has been rapid. Total plant recovery is between 20% and 55% after the first season in an arctic willow-birch plant community (Wein and Bliss, 1973). Hence, there is considerable merit in leaving the spilled oil and not creating additional disturbance through cleanup activities. In determining whether extensive plant damage will result from a spill, it is important to know the toxicity of the oil. Straight chain paraffins are the least toxic, while olefins, naphthenes, cycloparaffins and aromatics are of increasing toxicity, in that order. Within each of the above groups, oils with smaller molecules are more toxic than oils with larger molecules.

Spill cleanup need not necessarily take the form of immediate revegetation. Oil spilled in winter may be scraped from the snow and ice if the pour point of the oil is high; this technique would result in very little surface disturbance, and the need for revegetation could be greatly reduced if heavy equipment damage is minimal. Oils with lower pour points and oil spilled in the summer will naturally flow to the lowest point and must be contained; the disturbances created to contain these oils will usually require revegetation.

From the above discussion it is evident that there may be merit in leaving spilled oil, avoiding the creation of extensive landscape scars through cleanup operations. The personnel involved in spill cleanup must be cognizant of alternatives.

To aid the restoration of a site that has been damaged by a highly toxic spill, bacteria have been used to break down the phytotoxic components of the oil. It has been demonstrated that bacterial numbers, fungal mycelium, and soil respiration all increase after an oil spill (Wein and Bliss, 1973); thus, it is felt that these organisms are aiding in the decomposition of the oil. To encourage the natural microbial growth, and hence the breakdown of oil, seeding of microbial spores may be beneficial, as well as increasing the available nitrogen and phosphorus (Wein and Bliss, 1973; Jobson et al., 1974; Gudin and Syratt, 1975; and Lehtomäki and Niemelä, 1975).

Irrigation and aeration, in the form of discing or harrowing have been successful in accelerating the microbial breakdown of oils. Gudin and Syratt (1975) also suggest that covering the soil with black plastic in winter to increase temperature and clear plastic in the summer to reduce water loss will enhance microbial degradation. Much of the literature concerning microbial degradation stems from research done in temperate environments. However, the same principles may be useful for cold-region oil spills, with special considerations for arctic conditions.

The primary concern of any restoration is the prevention of offsite environmental deterioration in the form of accelerated erosion. In the case of cold regions wehre soils are underlain with permafrost, the minimization of the alteration of soil thermal regimes and the inherent melting of permafrost are important objectives of restoration.

SELECTION OF SPECIES FOR RESTORATION

As a rule, in any revegetation program, native species should be given first consideration in the formulation of the seed mix, and introduced species utilized only for special circumstances. Bliss (1979) states that the most successful revegetation programs have started by determining the role of native species in plant succession, and where possible these species have been incorporated in the seed mix. Native plants generally exhibit the following advantages over non-native or introduced species:

1. Because of natural selection and evolution, the native flora can be considered the best adapted to the environment of a site; thus, a seeding of natives should be a self-perpetuating plant community.

2. As a result of the evolutionary process, diverse native plant communities have developed a resistance to pests and disease to which large

monocultures of introduced species may be susceptible.

3. Native plants have co-evolved with native wildlife; thus, they should better serve the wildlife species of the area. In addition, a diverse native plant community is less subject to total annihilation by the local wildlife than is a monoculture of an introduced species.

4. The native plants that are adapted to a site have adapted to survive the most severe site conditions. This is especially important in arctic revegetation where winter hardiness is one of the major concerns.

5. Native plants do not represent a threat to surrounding plant communities, as might happen with introduced weedy species that thrive for a short period to the detriment of surrounding native plants and then perish during an extreme in temperature or insect pest invasions.

In spite of the adaptive advantages that native species have, the use of agronomic species cannot be overlooked in a restoration program. Depending upon the objectives of revegetation, agronomics may be better suited if an area is going to be returned to domestic utilization. Agronomic species are generally quicker to stabilize an area (Johnson and Van Cleve, 1976); thus they may be useful for rapid stabilization and erosion prevention. Agronomic species may also be useful as a nurse crop planting to enhance the establishment of more desirable native perennial species. Long-term objectives may also be fulfilled if native species are simply allowed to reinvade as the agronomics die out. A distinct advantage of agronomic species is that seed for them is readily available, whereas seed for most native species suitable for cold-region revegetation is in very short supply.

Table 27 lists species for revegetation on which research has been carried out, with indications of suitability. Distinctions have not been made between native, introduced, or agronomic species. Even though a species such as Arctagrostis latifolia, tall arctic grass, is a native to arctic areas, it could be considered introduced in subarctic areas.

CULTURAL PRACTICES

Seeding

After selecting the species for use in a restoration program, the source of the origin of the seed on transplant material must also be checked. The origin of seed for each species must be as close to the site as possible; genetic differences exist in each species, and by choosing a seed source as close to the location of use as possible, slight genetic adaptations to environmental factors can be accounted for. For example, if it is decided to seed bluejoint reedgrass Calamagrostis canadensis on a cold-region spill, the seed source should be from a location as close to the disturbed site as possible. Bluejoint is a common subalpine grass throughout the Rocky Mountains, and if seed for a subarctic spill originated in the Colorado Rockies, it would not be expected to do well. Purity, germination, and the certification of the seed should also be checked where possible. Timing of seeding is critical, and

TABLE 27. REVEGETATION SPECIES UNDER INVESTIGATION

Common name	Botanical name	Applicability	Source
Tall arctic grass	Arctagrostis latifolia	Arctic forage grass; saturated peats	Klebesadel, 1969 Johnson & Van Cleve, 1976
Cottongrass	Eriphorum vaginatum	Supersaturated mineral soils	Wein & McLean, 1973
Bluejoint reed grass	Calmagrostis canadensis	Peat soils; tundra; subarctic	Wein & McLean, 1973
Actared fescue		Arctic	Johnson & Van Cleve, 1976
Nugget Kentucky bluegrass	Poa pratensis	Arctic	Johnson & Van Cleve, 1976
Slender Wheatgrass	Agropyron trachycaulon	Arctic	Johnson & Van Cleve, 1976
Frontier reed canary grass		Arctic	Johnson & Van Cleve, 1976
Creeping bentgrass		Arctic	Johnson & Van Cleve, 1976
Creeping red fescue	Festuca rubra	Subarctic	Johnson & Van Cleve, 1976
Meadow foxtail	Alopecurus pratensis	Subarctic	Johnson & Van Cleve, 1976
Frontier reed canary grass	Phalaris arundinaceae	Subarctic	Johnson & Van Cleve, 1976
Durar hard fescue		Subarctic	Johnson & Van Cleve, 1976
Icelandic poa		Subarctic	Johnson & Van Cleve, 1976

(continued)

TABLE 27 (concluded)

Common name	Botanical name	Applicability	Source
Legumes		Ability to fix N_2; S. of 65° 21'	Johnson & Van Cleve, 1976
Alsike		Natural in Fairbanks, AK area	Neiland, 1978
Red clover	Trifolium pratense	Natural in Fairbanks, AK area	Neiland, 1978
Green alder	Alnus crispa	Ability to fix N_2	Klebesadel, 1978
Soapberry	Shepherdia Canadensis	Ability to fix N_2	Klebesadel, 1978
Silverberry	Eleagnus commutatus	Ability to fix N_2	Klebesadel, 1978
Bog myrtle	Myrica gale	Ability to fix N_2	Klebesadel, 1978
Ryegrass	Lolium multiflorum	Ability to fix N_2	Klebesadel, 1978
	Dupontia fischeri	Tolerant to crude oil	Deneke et al., 1975
Engmo timothy	Phleum pratense	Northern limit of open woodland	Bliss, 1979
Sheep fescue	Festuca avina		Bliss, 1979
Meadow fescue	Festuca elatior		Bliss, 1979
Fowl bluegrass	Poa polustris		Bliss, 1979

according to the Soil Conservation Service's Vegetation Guide for Alaska, seedings should be made from May 15 to June 15 for best results; successful seedings have been made later in the year, but the seedlings are more susceptible to winterkill. Annual rye grass and cereal crops, which may be used to provide temporary cover to reduce erosion, may be seeded as late as September 1.

Methods of seeding include drill seeding, hydroseeding, and broadcasting. The best method on nearly level or slightly sloping land is drill seeding, according to the Soil Conservation Service (1972) publication. Generally, heavy-duty drills, such as a rangeland or brillion drill, must be used to negotiate rocky or uneven terrain. When seeding with a drill the seed should be sown no greater than one-half inch in depth and the seedbed should be firmly packed for best seed/soil contact.

On slopes steeper than four-to-one, tractor-pulled drills are very difficult and possibly unsafe to use, and either hydroseeding or broadcasting are the other options. Hydroseeding involves spraying the seed with the fertilizer, if it is needed, in a water slurry. Specific recommendations for procedures should be obtained from the operator before use, because there is considerable variability in the equipment used for hydroseeding. Broadcasting, either by hand or aerially, has been used effectively, and, in the case of remote areas where oil spills may occur, this method is possibly the most practical. If broadcasting seed by hand, seed should be harrowed or raked into the soil and the seedbed packed. It is difficult to get good seed soil contact when broadcasting; thus, the seeding rate should be doubled as compared with a seeding rate for drill seeding (Soil Conservation Service, 1972). Obtaining the proper equipment for the first two seeding methods are the obvious drawbacks; thus, hand-broadcasting seems the most feasible alternative in remote arctic areas.

Seedbed Preparation

A proper seedbed may be critical to the success of establishing a stand of grasses. Deneke et al. (1975) experiments discussed previously made it apparent that seeding on top of the organic mat present in most arctic situations was of little use. Thus, the organic mat must be removed and seed sown in the mineral soil. If part of the dead vegetation or organic mat is worked into the mineral soil, this may enhance the seedbed. Ideally, the seedbed should be tilled so that it is weed-free and friable enough to permit seeding operations. On steep slopes or rocky soils, seedbeds must be as well prepared as possible. Johnson and Van Cleve (1976) state that the main problem in revegetation on an arctic or subarctic oil spill is establishing a good soil-plant moisture relationship, and proper seedbed preparation is possibly the best technique of enhancing this relationship.

Alternatives to Seeding

Because seed sources for many species are very limited, revegetating with other methods such as sprigging, caring, sodding, and using containerized greenhouse-grown transplants may be feasible alternatives. Sprigging involves the harvesting of living rhizomes or stolons, cutting them into short segments, and then planting them. This method has advantages as there have been high rates of successful establishment in arctic situations (Johnson and Van Cleve, 1976), and the material can be harvested over a longer period of time. However, the disadvantages of sprigging are that it takes a tremendous amount of time to gather the materials, and often special equipment is necessary to handle these propagules. In addition, the plant materials are often bulky and difficult to store and handle.

Coring involves taking plugs of existing vegetation from sites surrounding the site to be revegetated. Rowell and McGill (1978) have had considerable success using sedge plugs on oil spills in Alberta; however, Johnson and Van Cleve (1976) do not report such favorable results.

Sodding has been used with success in both arctic and alpine situations, according to Webber and Ives (1978). Sodding not only works well for plant establishment but also aids in restoring the thermal balance of a site and possibly prevents thermokarst development. Problems with sodding are the source of sod and the expense.

Container-grown transplants are becoming more and more common for revegetation work. Transplanting was originally designed for reforestation projects, but many nurseries now grow species suitable for other revegetation efforts as well. Advantages are that plants can be propagated from cuttings, sprigs, or seed; under ideal greenhouse conditions, a few sprigs or a small amount of seed may produce a large number of plants in comparison with what would be necessary for a field planting. The disadvantages of containerized transplants are, again, cost, handling, and obtaining the stock (usually a 1- or 2-year lead time is necessary to produce sufficient stock quantities).

A distinct advantage of caring, sprigging, or using greenhouse-grown transplants is that these methods of re-establishment can be used without disrupting the organic mat of vegetation. And, as most authors have pointed out, the removal of the organic mat alters the thermal regime and causes slumping and extensive erosion. The effects of the oil from the organic mat on a containerized plant or core have not been studied.

Fertility

Most researchers in cold-region revegetation work agree that the native soils are inherently low in fertility. According to Johnson and Van Cleve (1976), optimum fertilizer levels have not been determined; however, they recommend fertilizing with nitrogen, phosphorus, and potassium while seeding, repeating applications on problem areas. McKendrick and Mitchell (1978) have found a very significant response to phosphorus fertilizer. Deneke et al. (1975) have found liming and manuring beneficial as well as fertilizing. Spilled oil will often provide some of the fertility requirements; however, much research needs to be conducted concerning the availability of these nutrients. Soil testing is the best method to determine the rate of application for fertilizers. The fertilizer rate will also be dependent on the land-use objectives for the restored site; for example, if there will be intensive grazing on the site or other agricultural use, fertilizer rates will have to be considerably higher.

Mulching

Very little research work has been done with mulchers and mulching techniques as aids in enhancing the re-establishment of arctic or subarctic vegetation. However, Johnson and Van Cleve (1976) state that on gravel substrates, revegetation may be limited because of low soil moisture, and that mulches would improve this moisture regime, improve thermal stability of a site, and be beneficial to the nutrient regime.

Mulches are very important for the control of erosion while a vegetative cover is being established; thus, on steep slopes the Soil Conservation Service (1972) considers mulches essential. They suggest common types of mulch materials such as hay, small-grain straw, a straw-asphalt mix, wood fiber mulches, peat moss, gravel, or jute matting. Locally harvested grass, or grass hay, may be of considerable value as a mulch, because it often contains viable seeds. Mulch application can be done by hand on small areas or with the use of blowers or hydromulchers. Generally, if the mulch is a straw or hay mulch, it must be tacked to the soil surface to prevent wind blow. This tacking can be done mechanically with a crimper, with a tacking agent such as asphalt, or covered with some form of mesh or netting. Mulching must always be done after seeding to ensure that the seed has good contact with the soil; in some cases, where hydroseeding and hydromulching have been conducted, the seed, mulch, and fertilizer have been applied in one application, and the results were very poor. Mulching is generally an expensive procedure, especially in arctic situations where material availability is a problem; thus, the question of using a mulch must be thoroughly addressed with respect to the objectives of the revegetation effort.

Long-Term Management

Long-term management practices should be dictated by the initial determination of objectives for a revegetation program. Practices such as herbicide treatment or bush cutting may be necessary considerations for long-term management. Irrigating and repeated fertilizing also may be considered necessary procedures for the management of a revegetated area. Interseeding or the interplanting of greenhouse-grown containerized shrubs, grasses, or forbs may also be a very successful method of establishing a diverse, self-perpetuating, native plant community, and this interplanting can be done after the initial establishment of the protective vegetative cover. Long-term management also may consist simply of monitoring an initial revegetation effort for future information.

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